Human Gaze Control during Walking over Obstacles

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Summary

In human life, safe locomotion is essential for an independent living in the community. Several variable conditions in the environment require adaptation of gait parameters. Therefore, intact sensory inputs from somatosensory, vestibular and visual systems and the complex integration of this information in cortical motor planning are needed. An impairment of one of these inputs has to be compensated by the intact sensory systems or behaviour has to be changed. Otherwise, the risk of falling may increase. In this thesis, we investigated the influence of impaired sensory inputs on gaze behaviour during walking on a treadmill with an obstacle avoidance task. We analysed head-movements and gaze-movements (as a combination of head- and eye-movements) by a video-oculograph with an additional infrared-sensitive video camera, which detected infrared LEDs defining a coordinate plane on a floor plate.

With age, various sensory systems are reduced. So, in the first study, gaze behaviour of healthy elderly subjects was compared to middle-aged and young subjects. Elderly subjects turned their gaze earlier and longer to the obstacle than younger subjects. They could use the peripheral vision as less. We concluded that elderly subjects were more dependent on visual inputs. These results were consistent with earlier studies and therefore, the validity of our methodological approach could be confirmed.

In the second study, the influence of impaired somatosensory inputs in patients with an incomplete spinal cord injury (iSCI) on gaze behaviour was investigated. These patients showed good motor but reduced somatosensory functions. In a high-precision condition, in which subjects had to step over the obstacle with a low vertical foot clearance, iSCI-patients showed less flexible gaze behaviour compared to age-matched healthy subjects. They turned their gaze to the obstacle later and could not reduce the foot clearance. We concluded an augmented dependency of iSCI-patients on postural stabilising effects of a stable visual target.

In the third study, gaze behaviour was investigated in patients with a complete unilateral vestibular loss. We hypothesised that these patients would reduce their head-movement for denying vestibular disturbances and for increasing postural stability. No significant differences in gaze behaviour and locomotor performance between the vestibular patients and age-matched healthy subjects could be detected. Obviously, the loss of one vestibular organ was compensated by the intact side.

In a fourth study, we tried to answer if a pitch head-rotation during stepping over an obstacle in healthy young and elderly subjects really causes a vestibular disturbance and consequently, affects dynamic balance. However, we could not find any unambiguous indications of disturbed balance and therefore, the question could not be answered clearly. In fact, gait performance seemed to be influenced rather by the shifting visual input during looking downwards.

Zusammenfassung

Sichere und unfallfreie Fortbewegung ist in unserer Gesellschaft wichtig, um im alltäglichen Leben integriert zu sein. Anpassungsfähigkeit des Gangmusters an verschiedenste Bedingungen der Umgebung ist dazu notwendig. Dies setzt ein komplexes Zusammenspiel von afferenten, sensorischen Informationen aus den somatosensorischen, vestibulären und visuellen Systemen und deren Umsetzung in eine adäquate motorische Planung voraus. Ein Ausfall eines sensorischen Systems kann eventuell durch eine erhöhte oder veränderte Aktivität eines anderen Systems übernommen werden. Ist dies nicht der Fall und kompensiert die betroffene Person ihr Verhalten nicht entsprechend, können Stürze die Folge sein. In der vorliegenden Doktorarbeit wurde untersucht, was für einen Einfluss ein reduziertes oder fehlendes sensorisches System auf das Blickverhalten beim Gehen und Hindernis-Überschreiten auf einem Laufband hat. Für das Messen von Kopfbewegungen und Blickbewegungen (als Kombination von Kopf- und Augenbewegungen) wurde ein Video-Okulograph benutzt. Mit Hilfe einer zusätzlichen infrarot-sensiblen Video Kamera (montiert am Video-Okulographen) und fünf Infrarot-LEDs auf einer Bodenplatte war es möglich, Kopf- und Blickbewegungen anhand eines Koordinatensystems zu analysieren.

Da mit dem Alter die sensorischen Systeme an Effektivität verlieren, wurde in der ersten Studie das Blickverhalten von älteren Leuten mit dem von jüngeren Personen verglichen. Personen aus der älteren Gruppe richteten ihren Blick früher und länger auf das Hindernis als jüngere Personen. Ausserdem konnten sie Informationen aus dem peripheren Blickfeld weniger nutzen. Aus den Resultaten schlossen wir auf eine verstärkte Abhängigkeit von visuellen Informationen bei älteren Leuten. Da die Ergebnisse mit anderen Studien übereinstimmten, konnte die gewählte Methode als valide bestätigt werden.

In einer zweiten Studie wurde der Einfluss von reduzierten somatosensorischen Afferenzen auf das Blickverhalten untersucht. Patienten[1] mit einer inkompletten Rückenmarkverletzung mit guten motorischen aber beeinträchtigten sensorischen

[1] In den deutschen Texten wird nur die einfache Bezeichnung von Personen benutzt. Es sind aber Frauen und Männer gemeint.

Funktionen wurden mit gesunden Probanden verglichen. Die Patienten konnten ihren Blick weniger flexibel nutzen, um zum Beispiel früher oder länger aufs Hindernis zu schauen bei einer Aufgabe, in der sie so tief wie möglich übers Hindernis steigen sollten. Vielmehr schienen sie auf den stabilisierenden Effekt durch das Schauen auf einen festen Punkt angewiesen zu sein.

In der dritten Studie wurde das Blickverhalten bei Patienten mit einem kompletten, einseitigen vestibulären Ausfall untersucht. Wir erwarteten, dass diese Patienten weniger aufs Hindernis schauen als gesunde Personen, um den Kopf besser zu stabilisieren. Diese Hypothese basierte auf der Annahme, dass eine Kopfbewegung nach unten einen vestibulären Reiz darstellt und somit zu einer Störung des dynamischen Gleichgewichtes führt. Die Resultate zeigten allerdings keine Unterschiede. Anscheinend konnten die Patienten den einseitigen Ausfall des Vestibulärsystems mit dem intakten Organ der anderen Seite kompensieren.

Die Ergebnisse der dritten Studie führten zu einer vierten Studie, in der wir den Einfluss der Kopfbewegung nach unten während des Überschreitens eines Hindernisses bei gesunden jungen und älteren Personen untersuchten. Die Frage, ob diese vertikale Kopfbewegung einen vestibulären Reiz auslöst, konnte nicht eindeutig beantwortet werden. Es wurde diskutiert, ob nicht vielmehr die durch das nach unten Schauen instabilen visuellen Afferenzen die Gangparameter beeinflussten.

1 General introduction

1.1 Locomotion during daily life

Movement in daily life is a small miracle. Normally, we are not aware of our locomotion and we manage to cope with many requirements without consciously noticing them: During walking, we are able to carry goods; we can talk and it is no problem to direct our attention to quickly changing environmental factors, such as traffic. Furthermore, during walking we have the ability to continuously update our orientation without stopping, we can adjust our walking speed to different situations and if required climb stairs, step over obstacles, and perform other adjustments for safe locomotion. We are not aware of these daily movements until a situation becomes unusual as, for example, when we have to walk over an icy or other highly challenging underground, or when we become injured and suddenly a certain movement hurts. In the extreme case, patients have to relearn walking movements during rehabilitation after they have suffered from an orthopaedic or neurologic disease, such as after a stroke or a spinal cord injury. Here, walking is not automated anymore and it requires continuous cognitive attention to perform steps (Mulder and Geurts, 1993).

Knowledge about the mechanisms of daily locomotion is essential to improve the quality and the efficacy of a rehabilitation therapy. A main point – if the severity of the disease allows - is to regain safe locomotion for daily life, i.e. walking without falling. Falls are a serious problem in our community as they may cause injuries. In a review about falls among elderly people, Grob (2005) reported a medical consultation after almost 30 % of falls. This also leads to considerable economic costs, especially as falls in elderly people often lead to rehabilitation and long-term care (Seematter-Bagnoud et al., 2006). Additionally, falls may cause fear of falling resulting in augmented difficulty to participate in social life (Vellas et al., 1997).

Possible causes for falls in daily life are obstacles such as curbs, uneven or loose cobblestones, steps, or even cats and dogs which cross the path unexpectedly (David and Freedman, 1990; Hill et al., 1999; Stevens et al., 2010). Challenges in obstacle avoidance compared to straight over-ground walking are the possible stumble of the swing limb on the obstacle and an elongated single stance phase during which the centre of mass is outside of the base of support (Austin et al., 1999). So, the goal for a successful rehabilitation therapy after an injury should not simply be the improvement of unobstructed over-ground walking, but also the training of relevant daily situations such as obstacle crossing. Therefore, information about locomotion trajectories, motor outputs and sensory inputs are needed.

1.2 Sensory inputs

Successful multifunctional locomotion, as described in chapter 1.1, requires complex motor control. Afferent sensory inputs from the periphery must be integrated in the brain to update the motor plan resulting in efferent motor outputs (Shumway-Cook and Woollacott, 2001). Therefore, sensory information from the environment and the position of the body in space is processed by three main inputs: the somatosensory system, the vestibular system and the visual system (Shumway-Cook and Woollacott, 2001). The somatosensory system may be classified in proprioception, exteroception and interoception (Schmidt, 1995). Proprioception provides information about joint positions and joint-movements. Exteroception is responsible for haptic sensations, for example the pressure of vertical ground forces on the sole of foot. Interoception is the inner body sensory system for the viscera and may be less relevant for daily movements. The vestibular system with its three semicircular canals and the two otolith organs located in each inner ear is responsible for orientation in space and information about head position by measuring circular and linear head acceleration (Schmidt, 1995). Somatosensory and vestibular senses are only self-motion perceptions, whereas visual inputs can give information about self-motion and object-motion. Therefore, the visual system allows us to receive a three-dimensional perception in a forward manner, i.e. we get information about our distant environment allowing proactive adjustments (Patla, 1997).

These three sensory inputs do not operate separately, but interact with each other. A proof for the interaction between the vestibular and visual system is given, for example, by the study of Deutschländer et al. (2002). During vestibular stimulation, cortical brain areas responsible for vestibular information were activated while visual cortical areas showed a deactivation. During visual stimulation, activation and deactivation of cortical areas were inverted. These two brain areas work in a reciprocal inhibitory interaction system. Other studies have shown that the visual information is the dominant sensory input for balance and locomotion in humans (Collins and De Luca, 1995; Patla, 1997). If there is a mismatch between, for example, vestibular and visual information, visual input "overwrites" the vestibular one (Kennedy et al., 2003).

1.3 Gaze behaviour and locomotion

As described in chapter 1.2, visual input is one of the most important sensory inputs for human locomotion. Nevertheless, safe locomotion does not need a permanent visual input. During over-ground walking, intermittent visual sampling of the pathway in a feed-forward mode is adequate (Assaiante et al., 1989; Patla et al., 1996; Thomson, 1983). On even terrain, a visual sampling of the ground for less than 10 % during travel time (without initiation and termination of walking phase) is sufficient (Patla, 1997). However, increased sampling is required for more challenging conditions. For example, in a constrained situation when subjects were told to step on specific locations, the need for sampling increased to 30 % (Patla, 1997). In a similar task during stepping on given targets, the gaze of subjects was directed on the floor on average two steps ahead and was "carried along with the body", the so called "travel fixation", during most of the travel time (Patla and Vickers, 2003).

In an obstacle avoidance task, travel time can be separated in two phases: the approaching to and the crossing over the obstacle. In the approaching phase, participants fixate the obstacle for about 20 % of the travel time and the number of fixations rises with the height of the obstacle (Patla and Vickers, 1997). During the crossing step, normally no gaze turn to the obstacle occurs indicating that planning for the obstacle step is performed in a feed-forward manner. In fact, during crossing the obstacle, the gaze is already directed behind the obstacle for planning of future steps (Patla and Vickers, 1997). However, during obstacle crossing, peripheral vision plays an important role, as the vertical foot clearance is increased in conditions with restricted lower visual field. This fine-tuning of foot clearance occurs not in a feed-forward, but an online mode (Patla, 1998).

1.4 Aim of the thesis

Based on the importance and dominance of the visual system as a sensory input during locomotion (see chapter 1.3) and based on the augmented demand and the daily relevance of obstacle avoidance (see chapter 1.1), the focus of this thesis was to investigate gaze behaviour during walking over obstacles. Elderly healthy subjects and patients with neurological diseases such as vestibular loss or spinal cord injury were investigated representing a population with an increased risk of falling. The main question was if the impaired sensory inputs in these groups lead to compensatory alterations in gaze behaviour.

1.4.1 Elderly people

The risk of falling increases with age (Gostynski et al., 1999). Several studies have investigated the incidence of falls in elderly and reported one or more falls in about one third of the participants (Blake et al., 1988; Stalenhoef et al., 2002; Stel et al., 2004; Tinetti et al., 1988). About 30 to 40 % of falls resulted in minor injuries, 15 to 25 % in severe injuries, and 6 % in fractures (Grob, 2005). So, as a consequence of falls in elderly people, health costs are increasing, especially as our community is getting older. A further problematic consequence of falls in daily life is the psychological aspect for the subject. For 32 % of elderly persons who already had a fall, Vellas et al. (1997) reported a fear of falling resulting in reduced social and physical activities (Stel et al., 2004).

Several risk factors for falling in elderly people are mentioned: muscular weakness, gait disturbances as elongated double stance phases, unsteadiness, stiffness, reduced and more variable cadence, balance disorders, decline in body-orientation reflexes, constraint in cognitive capability, medications, and others (Grob, 2005; Lord et al., 1996; Rubenstein, 2006). Wong et al. (2008) gave the statement: “Elder fallers may have a higher propensity to consciously control their movements.” Therefore, we wanted to know if healthy elderly people – who can be considered as a group with a higher risk of falling – show altered gaze behaviour compared to younger subjects. As there already are some studies about gaze behaviour in elderly subjects (Chapman and Hollands, 2006; Di Fabio et al., 2003; Marigold and Patla, 2008a; Yamada et al., 2010), we had the possibility to confirm these results and validate our experimental approach (see chapter 1.5) as we could compare our results with the existing literature. The study of gaze behaviour in elderly, middle-aged and young subjects is reported in chapter 2.

1.4.2 Incomplete spinal cord injured patients

The worldwide incidence for a spinal cord injury (SCI) is between 10.4 and 83 per million inhabitants per year (Wyndaele and Wyndaele, 2006). An extrapolation from the incidence in the United States to all developed countries shows a further SCI all 16 minutes (Raineteau and Schwab, 2001). In about 50 % of the cases, the spinal cord lesion is incomplete (Wyndaele and Wyndaele, 2006), i.e. some ascending sensory and /or descending motor information is still conducted from the periphery to the brain and vice versa, respectively. Patients with an incomplete spinal cord injury (iSCI) may achieve a certain ability to walk due to intensive rehabilitation (Dobkin et al., 2006). Often, walking aids are required and multiple compensatory strategies are necessary to ambulate (van Hedel et al., 2008). However, sometimes the gait performance is so good that one could not even see any handicap. Nevertheless, impaired proprioception, vestibulo-spinal conduction and / or reduced muscle strength lead to a high risk of falling in iSCI-patients. Brotherton et al. (2007) reported at least one fall over one year in 75 % of the participants with iSCI, while Wirz et al. (2010) reported that 62 % suffered from a fall.

For our study of gaze behaviour we investigated iSCI-patients with good motor functions, as they had to be able to walk on a treadmill and step over obstacles, but with impaired somatosensory functions. Thus, we were able to investigate the influence of reduced proprioception on the visual behaviour. To simulate a high demanding walking condition, a dual task condition was added simulating a cognitive action during walking as, for example, a conversation. The aim of the study was to gain knowledge about the gaze behaviour in iSCI-patients and to translate possible findings from this experimental approach to the clinical rehabilitation training. The study is described in chapter 3.

1.4.3 Patients with a vestibular loss

The vestibular system senses head-motion and head orientation in space in relation to gravity. The vestibular organs are not working separately but interact with, for example, the visual system for stabilisation of the retinal image by the vestibulo-ocular reflex (VOR) (Schmidt, 1995). We are not aware of the vestibular system under normal daily conditions despite its permanent inputs which are important for our postural stability. Vestibular diseases or a neurectomy (the surgical removal of (a part of) a vestibular organ or a cut of the vestibular nerve), for example, due to a removal of a tumour, may lead to an incomplete or complete loss of vestibular functions. This loss can be on one or both sides, i.e. a unilateral or bilateral loss. Such a vestibular loss is a great challenge for the affected individuals. In the acute phase, dizziness and nausea can lead to problems in daily life activities and, therefore, to the impossibility of participation in the community. Despite of possible compensations in the chronic phase (Borel et al., 2004; Borel et al., 2002), the incidence of falls is increased. In two studies, falls in 30 % to about 50 % of patients were reported, depending on unilateral or bilateral loss (Ganança et al., 2006; Herdman et al., 2000). In another longitudinal study, 80 % of patients in an accident and emergency hospital with an unknown cause of fall had symptoms of a vestibular impairment (Pothula et al., 2004). In the study in chapter 4, we investigated if patients with a complete unilateral vestibular loss compensate their impaired vestibular input with altered gaze behaviour.

1.4.4 Pitch head-rotation

In the fourth study (chapter 5), we investigated vertical head-movements (i.e. pitch head-rotation) during stepping over an obstacle in healthy young and elderly subjects. We wanted to know if this head-movement in the sagittal plane causes vestibular stimulation resulting in balance disturbances. If yes, such head-movements might be problematic for patients with a unilateral vestibular loss. Therefore, pitch head-rotation was compared to a galvanic vestibular stimulation simulating a forward head-movement (see chapter 1.5) and to a stabilised head position. Several studies have shown that gait disturbances may be detected by, for example, variable double-stance phases or step length (Lord et al., 1996; Mbourou et al., 2003; Winter et al., 1990). So, we analysed gait parameters to obtain information about the influence of pitch head-rotation on walking trajectory during an obstacle avoidance task.

1.5 Description of experiments

To investigate the role of visual inputs and the association with diminished other sensory inputs on a demanding locomotion condition, we chose a repetitive obstacle avoidance task. Therefore, we used a split-belt treadmill and two obstacle machines (Fig. 1.1) as in several established studies with a different focus done in our laboratory (Erni and Dietz, 2001; Michel et al., 2009; van Hedel et al., 2002).

Figure 1.1: Obstacle avoidance wearing a video-oculograph. Subjects walked on a treadmill and stepped over an obstacle triggered by heel strike and announced with an acoustic warning signal. For detecting gaze-movements, subjects wore a video-oculograph.

The system allowed us to measure stepping over obstacles in recurrent consistent conditions and enabled enough repetitions for an accurate data analysis without exhausting participants and especially patients too much. Additionally, walking on a treadmill and therefore walking on a constant place gave us the possibility to secure participants with a safety harness. Force sensors located under the treadmill enabled measurements of vertical foot forces, i.e. detecting heel strikes and toe offs and therefore analyses of gait parameters such as duration of double stance phases or swing phases were possible. The obstacles could be triggered incidentally or by different events as, for example, by heel strike and they could be announced with acoustic warning signals. Infrared sensors attached to the obstacle machines enabled detection of the vertical foot clearance. Therefore, in combination with an acoustic feedback about the foot clearance, a high-precision obstacle avoidance task could be investigated. Further details are described in chapter 2 to 5.

There are several methods to investigate gaze behaviour as, for example, by intermittent light sources (Assaiante et al., 1989; Laurent and Thomson, 1988) or by using obstructive glasses (Patla et al., 1996; Patla and Greig, 2006). However, a direct measurement of eye-movements enables investigations of gaze behaviour under normal light conditions. Therefore, different systems may be used as, for example, the electro-oculography, the scleral search coil system, infrared-oculography or video-oculography (Eggert, 2007; Schmid-Priscoveanu and Allum, 1999). The latter one has the advantage of an easy application with hardly any restrictions for the participants enabling long lasting measurements during motor activities (Schneider et al., 2005). Two video cameras laterally attached to the frame of goggles detected the pupils for measuring eye-movements. As gaze is a combination of eye- and head-movement, in addition to the eye-tracking system we used a special setup for detecting head-movements. For more details, see the methods of the studies described in chapter 2, 3, and 4. From the data of the video-oculograph (VOG), we were specifically interested in where the subjects watched at (spatial parameters) and when or how long they watched (temporal parameters).

For the investigation in study four (chapter 5), we needed a vestibular stimulation for simulating a vertical head-movement (i.e. pitch head-rotation). In clinical assessments, often caloric vestibular irrigation with warm and cold water or gas is used for vestibular stimulation (Wuyts et al., 2007). However, for short lasting stimulations during walking, we preferred an electrical stimulation called galvanic vestibular stimulation (GVS) (Fitzpatrick and Day, 2004). GVS was performed by applying an electric current transcutaneously to the vestibular organs by placing electrodes behind the ears on the processi mastoidei. The stimulation results in the modulation of the afferent firing rates of the vestibular organs. Studies have shown that GVS has postural effects during standing by disturbing the balance (Fitzpatrick et al., 1994; Inglis et al., 1995). The influence of GVS is also detectable during walking inducing gait deviation towards the anode (Bent et al., 2000). Depending on the placement of anode and cathode, different simulations of head-movements are possible (Cauquil et al., 1998). The chosen method for our study is described more detailed in chapter 5.

2 Gaze strategies for avoiding obstacles: differences between young and elderly subjects[1]

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2.1 Abstract

Visual input is highly relevant for safely stepping over obstacles. In this study, gaze behaviour was investigated in elderly, middle-aged and young subjects as they walked on a treadmill repeatedly stepping over obstacles, which approached either on the right or left side. In between obstacle-steps, subjects visually fixated a target N or F located two or four steps ahead on the floor, respectively. An acoustic warning signal announced the obstacles, after which subjects were free to look wherever they wanted. Gaze-movements were measured by video-oculography. Four conditions with 20 obstacles were conducted (two with target N, two with target F). In two conditions, high-precision stepping was investigated by asking subjects to step with minimal foot clearance over the obstacles, while receiving acoustic feedback about their performance. In the high-precision conditions, more subjects (target N: 70 %, target F: 81 %) turned their gaze on the obstacles and for a longer time than in unrestricted conditions. When fixating on the near target N and unrestricted stepping over the obstacles, significantly more elderly subjects (85 %) turned their gaze on the obstacle compared to middle-aged (17 %) and young subjects (29 %).The elderly turned their gaze earlier and longer on the obstacle than middle-aged or young subjects. Our results reveal a different gaze behaviour strategy of elderly subjects suggesting a greater dependency on visual inputs.

2.2 Introduction

Safe locomotion allows independent mobility in daily life, but requires a complex interaction of somatosensory, vestibular, and visual inputs. The latter seems to play a dominant role (Kennedy et al., 2003; Patla, 1997). Diminished afferent functions increase

[1] This manuscript has been submitted to Gait & Posture. All measurements and analyses were conducted by Sandra Keller Chandra. The manuscript was written by Sandra Keller Chandra and revised by the co-authors.

the risk of falling. Moreover, people who have experienced a fall may develop a fear of falling, jeopardizing their independence. The elderly in particular are prone to falling, with an incidence between 28 % and 35 % (Blake et al., 1988; Buatois et al., 2006; Hill et al., 1999; Stalenhoef et al., 2002; Tinetti et al., 1988). Falls are frequently caused by stumbling over obstacles (Hill et al., 1999; Tinetti et al., 1988) such as uneven ground, curb stones or door steps (Austin et al., 1999; McFadyen and Carnahan, 1997).

Several studies have shown different gait behaviours between young and elderly subjects during walking over challenging pathways. The elderly walked slower and with shorter steps over multi-surface terrain, such as slippery or uneven grounds (Marigold and Patla, 2008b). Furthermore, they crossed an obstacle with a step more elongated than necessary for a safe landing position (Weerdesteyn et al., 2005a). Their success rate for safe obstacle avoidance was lower, the reaction time longer, the horizontal toe and heel distances to the obstacle were smaller, and the vertical foot clearance was larger than in young subjects (Weerdesteyn et al., 2005b). Elderly people adjusted their stepping pattern one step earlier than young subjects during walking over virtual obstacles (Chen et al., 1994).

Besides adjustments in gait parameters, gaze behaviour appears also to be altered in aged people during challenging walking tasks. When instructed to step precisely on given targets, elderly subjects visually fixated these targets earlier and longer compared to young subjects (Chapman and Hollands, 2006). During walking on a multi-surface terrain, elderly subjects needed more and prolonged visual inputs from the lower field than younger subjects (Marigold and Patla, 2008a). In an obstacle avoidance task with an additional cognitive challenge for selecting which limb crosses first over the obstacle, the elderly visually fixated the place where the leading foot should land for a longer time compared to young subjects (Di Fabio et al., 2003). Moreover, elderly fallers turned their gaze away from the obstacle earlier than elderly non-fallers in a dual-task condition (Yamada et al., 2010).

The present study evaluates changes in gaze behaviour during repetitive stepping over obstacles, both during normal and high-precision conditions in healthy young, middle-aged and elderly subjects. This investigation adds information to the existing literature, as several methodological approaches previously applied are now combined into one study:

We evaluated changes in gaze behaviour (i) without restricting vision by using video-oculography, (ii) during repetitive obstacle steps with equal conditions for each step to improve measurement accuracy, and (iii) in three age groups. We hypothesised that (i) elderly subjects need more visual input and (ii) high-precision conditions require more visual control than unrestricted obstacle avoiding.

2.3 Methods

2.3.1 Participants

The experiment was approved by the Cantonal Ethic Commission Zurich. Participants gave informed and written agreement prior to data collection. Forty-four healthy subjects without orthopaedic or neurological disease participated and were classified in three groups: 17 subjects older than 60 years (average ± SD: 68.4 ± 5.5 years; range 63 - 81 years), all living independently and recruited at the Senior University Zurich; 12 middle-aged subjects (45.2 ± 5.5 years; range 35 - 53 years), recruited by advertisement via the internet, and 15 young subjects (24.0 ± 3.7 years; range 19 - 30 years), recruited via a student job platform. Only subjects who could see a 2 x 3 cm target on the floor 2.5 m in front of them were included. Contact lenses, but not glasses, could be worn under the video-oculograph.

2.3.2 Data collection

Treadmill with obstacle machines

Subjects walked on a split-belt treadmill (Woodway, Weil am Rhein, Germany) with two obstacle-machines (ALEA Solutions, Zurich, Switzerland) to study repetitive stepping over a right and a left foam stick, 18 cm above the floor (Erni and Dietz, 2001). Force sensors (Kistler, Winterthur, Switzerland) under the treadmill detected the right and left heel strike, which randomly triggered the start of the right or left obstacle, respectively. The inter-obstacle interval was 13 to 30 seconds. Simultaneous to this heel strike, the obstacle started to move with the same speed as the treadmill (2.5 km/h) and subjects had to cross it in the step after the next (about 1 s after the obstacle-trigger). The obstacle folded up at the end of the treadmill and moved back into the starting position about 70 cm in front of the subject (Fig. 2.1). Stumbling was prevented because the foam sticks folded back or were released when touched. At the time of obstacle-release, the subjects received a short acoustic warning signal. In the high-precision conditions (see 2.3.3 Protocol), the vertical distance between the crossing leading foot and the obstacle (i.e. foot clearance) was measured by infrared sensors attached to the obstacle machines. Corresponding acoustic feedback tones of different frequencies were given to the subjects defining six levels in 2 cm intervals between 0 cm and 12 cm.

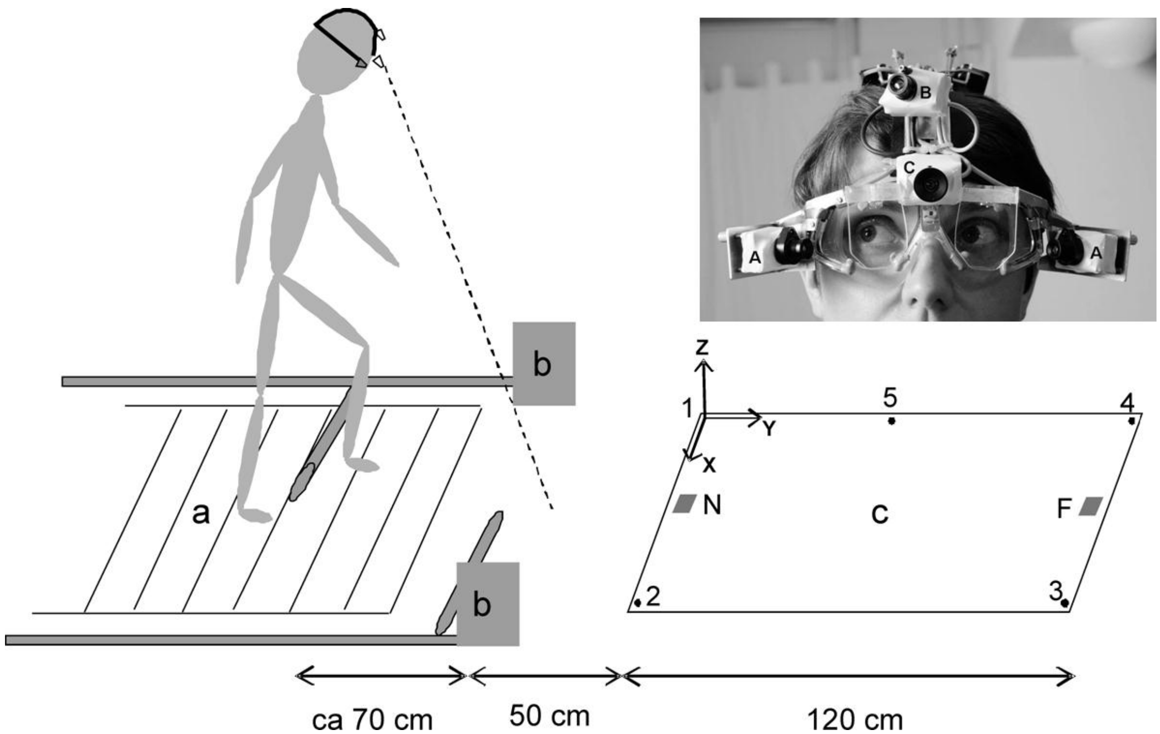

Figure 2.1: Experimental setup and eye-tracking system. (a) treadmill, (b) obstacle machines and (c) floor plate. 1 – 5 = LEDs spanning a coordinate system with the origin at LED 1, N and F are the targets for gaze fixation during the interval between two triggered obstacles in the different conditions. Video-Oculograph (EyeSeeCam, Munich, Germany) with two eye-cameras (A), a gaze-driven head-camera (B) and an infrared-sensitive scene-camera (C)

Eye tracking system

A video-oculograph (VOG; EyeSeeCam, Munich, Germany) with a gaze-driven head-camera and an infrared-sensitive scene-camera was used for measuring gaze-movements (Schneider et al., 2005). Eye-movements were recorded by two eye-cameras (recording-frequency 76 Hz) laterally attached to the frame of the goggles without restricting the subject’s view (Fig. 2.1). These cameras recorded movements of the pupils via two transparent mirrors. The gaze-driven head-camera (recording-frequency 30.4 Hz) was aligned parallel to the eyes by servo drivers continually updated based on the eye-movement data. The infrared-sensitive scene-camera (recording-frequency 76 Hz) was used to measure head-movements (see setup below).

Setup

A floor plate in front of the treadmill was equipped with five infrared LEDs lying in a plane (Fig. 2.1). The LEDs were invisible for human eyes but could be detected by the infrared-sensitive scene-camera. By knowing the position of the plane in relation to the environment, the head position (head-on-plane), i.e. where the infrared-sensitive scene-camera pointed on the floor, could be detected. By combining the data of eye- and head-movements, the gaze fixation points (= gaze-on-plane) on the floor could be determined.

Variables

Recorded and analysed were the vertical forces on the treadmill for detecting heel strike and toe-off, the obstacle trigger signals, foot clearance, gaze-on-plane, head-on-plane and the video of the gaze-driven head-camera.

2.3.3 Protocol

Prior to the experiment, subjects were familiarized with walking on the treadmill and stepping over the obstacles. The walking position and / or the obstacle machines were positioned in such a way that subjects were able to step over the obstacle without changing their step-rhythm. The walking speed was 2.5 km/h.

After the VOG was calibrated, the subjects performed four conditions with 20 obstacles each. In-between two triggered obstacles, subjects were instructed to gaze at a 2 x 3 cm target fixation point located on the floor plate. As soon as the obstacle was triggered and the acoustic warning signal sounded, subjects were free to look wherever they wanted. In condition N (near), subjects had to look at the near target about two steps ahead during the time in-between two triggered obstacles. We assumed that peripheral vision could be used in this condition. In condition N+P (precision), subjects looked at the same target N, while they performed a high-precision stepping task, i.e. they had to step over the obstacles with minimal foot clearance, receiving acoustic feedback about their performance. In condition F (far), subjects had to look at target F, located about four steps ahead. In this condition, we assumed that it was difficult to use solely the peripheral vision. Condition F+P was the same as N+P but with target F. The order of the conditions was randomised.

2.3.4 Data analysis

In the raw gaze data, artefacts and blinks were eliminated by a 5 Hz median filter. Data from steps in which the obstacle was touched were not analysed. For each subject and condition, the median gaze-on-plane and head-on-plane was calculated between 1.3 s before and 3.9 s after the obstacle-trigger for all 20 obstacle steps for the right and left sides separately. Then, the right and left median gaze-on-plane and the right and left median head-on-plane were averaged, respectively. Several gaze-characteristics were derived from the sagittal data (Fig. 2.2): (i) the amplitude of gaze- and head-movement downwards, (ii) the latency between the obstacle-trigger and the onset of gaze- and head-movement downwards, and (iii) the duration between the onset of gaze- and head-movement downwards and redirection upwards. To minimise the subjectivity in determining these events, the analyses were performed by two investigators. If small differences between the events were found, the average was taken into the analysis. Large differences were analysed a third time.

Three gaze-patterns were identified (Fig 2.2): Pattern 1 – gaze-direction on the obstacle (amplitude ≥ 40 cm for the near target N or ≥ 155 cm for the far target F); Pattern 2 – gaze-direction towards the obstacle, but not completely (amplitude between the defined limits of gaze-pattern 1 and 3); Pattern 3 - gaze was not turned away from the given target (amplitude ≤ 10 cm for the near target N or ≤ 15 cm for the far target F). These borders were determined on the basis of 66 control measurements. Gaze-pattern 2 was additionally verified by studying the gaze-driven video images and the examination of the gaze-on-plane data for each individual obstacle step, before calculating the median. If head or gaze was not turned downwards (i.e. gaze-pattern 3), amplitude and duration were set to 0 cm and 0 s, respectively, latency was defined as a missing value.

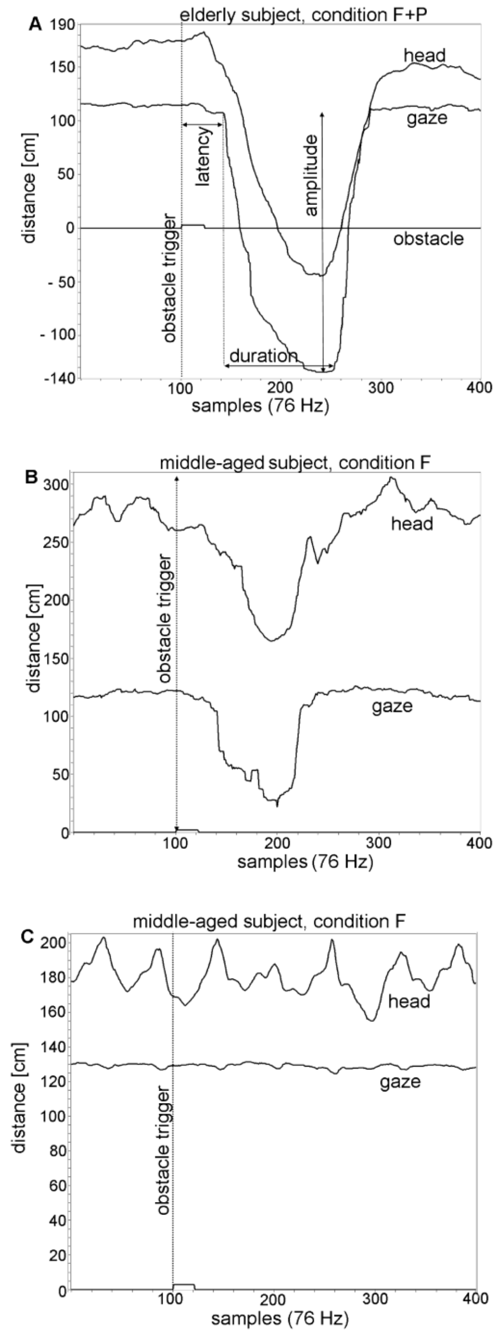

Figure 2.2: Three examples of head-on-plane and gaze-on-plane in relation to the obstacle trigger. The plots are averaged left and right medians of all obstacle steps in one subject in a single condition. The upper trajectory shows the head-on-plane [cm], the lower trajectory gaze-on-plane [cm]. Example A illustrates a gaze-pattern 1 (gaze-turn to the obstacle), B illustrates a gaze-pattern 2 (gaze-turn into the direction of the obstacle), and C a gaze-pattern 3 (no gaze-turn to the obstacle). About one second after the obstacle-trigger, subjects crossed the obstacle.

Most data were not normally distributed and the group sizes were small, therefore, nonparametric statistical tests were used. The three gaze-patterns were considered as ordinal data. For the pair-wise comparison between the three age groups, the Mann-Whitney-U Test was used. For the pair-wise comparisons between the conditions (N vs F, N+P vs F+P, N vs N+P, F vs F+P) the Wilcoxon Test was applied. To adjust for multiple comparisons, the significance-level was set at 0.025, and 0.05 was interpreted as a tendency.

2.4 Results

One-hundred-sixty out of 176 datasets (4 conditions x 44 subjects) could be analysed. The rest were of insufficient quality due to recording problems (e.g. no pupil detection because of closed eyelids). Results are presented in Tables 2.1 and 2.2.

2.4.1 Gaze-patterns

Overall, more subjects turned their gaze on or into the direction of the obstacles in the high-precision conditions N+P and F+P than in condition N and F, respectively. In the subgroups, more young and middle-aged subjects turned their gaze on or into the direction of the obstacle in condition N+P compared to N. More elderly subjects tended to turn the gaze downwards in condition F+P compared to F. The group-comparison in condition N showed that more elderly subjects turned their gaze on or into the direction of the obstacles compared to the number of middle-aged subjects and young subjects.

2.4.2 Gaze- and head-amplitudes

In the high-precision conditions, subjects showed increased gaze- and head-amplitudes downwards. In condition N vs N+P, this was also observed for the subgroups (except for head-amplitude in the elderly), while in F+P vs F the difference was only significant in the young group. In condition N, larger gaze- and head-amplitudes were found in elderly compared to middle-aged subjects and a larger gaze-amplitude compared to young subjects. In condition F, elderly showed a larger head-amplitude compared to middle-aged subjects.

When analysing gaze-pattern 3 including all subjects and conditions, 31 % of the subjects showed no significant gaze- and head-amplitude, 10 % showed a small (still in the defined range for gaze-pattern 3), but still larger gaze-amplitude than head-amplitude, and 59 % showed a larger head-amplitude than gaze-amplitude.

2.4.3 Gaze- and head-latencies

Except for condition F, the gaze-latencies were shorter in the elderly compared to the middle-aged and young subjects (only a tendency in condition N compared to young subjects) (Fig. 2.3). Head-latencies were shorter in conditions N+P and F in the elderly compared to the middle-aged subjects.

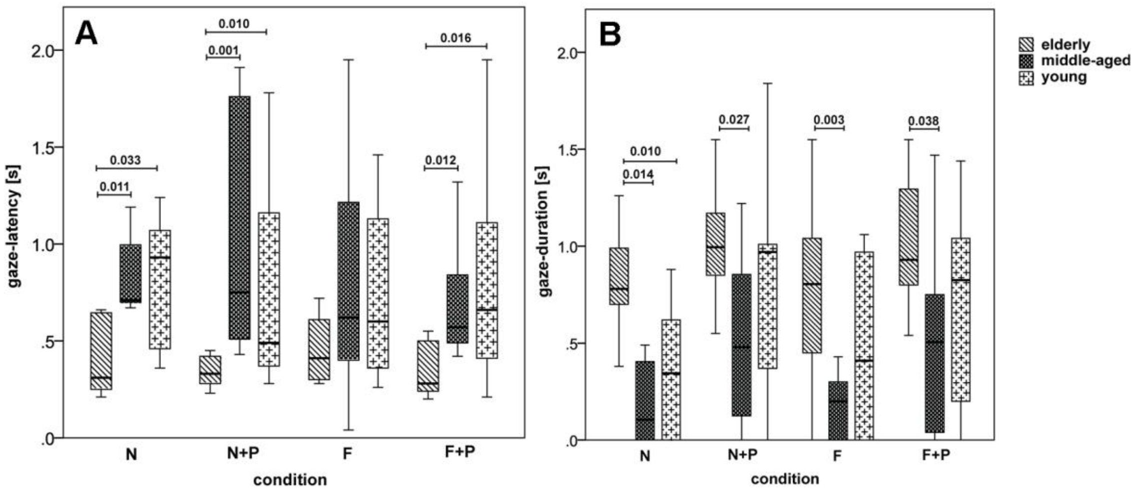

Figure 2.3: Box plots of gaze-latency (A) and gaze-duration (B). Box-plots represent the median value (dark stripe within the box). The lower whisker represents the lower 25 % of the observations; the box represents the intermediate 50 % of the observations and is divided by the median, which divides the observations in the upper and lower 50 %; the upper whisker represents the upper 25 % of the observations. The values indicate the p-values for significant comparisons ($p < 0.025$) or for tendencies ($0.025 < p < 0.05$). Abbreviations: N = condition with visual fixation point two steps ahead, F = condition with visual fixation point four steps ahead, N+P = condition with visual fixation point two steps ahead and high-precision obstacle-avoidance, F+P = condition with visual fixation point four steps ahead and high-precision obstacle-avoidance.

2.4.4 Gaze- and head-movement-durations

Over all subjects, prolonged gaze- and head-movements to the obstacle were observed in the high-precision conditions. Prolonged gaze- and head-movements were found in condition N+P compared to N in young subjects. In other groups, some tendencies could be found for prolonged gaze- and head-movements in the high-precision conditions. In all conditions, elderly subjects gazed longer at the obstacle than middle-aged subjects (tendencies in conditions N+P and F+P). In condition N, elderly gazed longer compared to young subjects (Fig. 2.3). The head pointed longer to the obstacle in elderly than in middle-aged subjects in conditions N and F.

2.4.5 Foot clearance

In the high-precision tasks, all subjects together showed a significantly smaller clearance than in the low precision tasks. This result was confirmed in the three subgroups (N vs N+P: tendency in the middle-aged group). The foot clearance was smaller in condition N than in F over all subjects. In the subgroups, tendencies for the young and middle-aged groups were found. The young subjects showed a smaller foot clearance than the elderly in the high-precision conditions.

Table 2.1: Statistical significance for comparison between groups and conditions

		Gaze-pattern	Amplitude head	Amplitude gaze	Latency head	Latency gaze	Duration head	Duration gaze	Clearance
N vs N+P	All subjects	0.001	<0.001	<0.001	0.683	0.767	<0.001	<0.001	<0.001
	Elderly	0.414	0.056	0.016	0.838	0.790	0.033	0.050	0.002
	Middle-aged	0.024	0.007	0.009	0.866	0.917	0.028	0.109	0.034
	Young	0.015	0.003	0.003	0.445	0.889	0.019	0.009	0.001
F vs F+P	All subjects	0.007	0.002	0.001	0.217	0.300	0.001	0.002	<0.001
	Elderly	0.038	0.221	0.071	0.142	0.307	0.142	0.169	0.002
	Middle-aged	0.248	0.114	0.182	0.036	0.917	0.037	0.050	0.005
	Young	0.096	0.006	0.008	0.153	0.374	0.034	0.060	0.007
N vs F	All subjects	0.243	<0.001	<0.001	0.100	0.153	0.317	0.993	0.011
	Elderly	0.206	0.006	0.028	0.508	0.790	0.689	0.374	0.950
	Middle-aged	0.059	0.017	0.032	0.249	0.043	0.333	0.906	0.028
	Young	0.096	0.050	0.034	0.400	0.249	0.722	0.307	0.031
N+P vs F+P	All subjects	0.819	<0.001	<0.001	0.456	0.557	0.881	0.451	0.368
	Elderly	0.564	0.001	0.003	0.969	0.666	0.087	0.271	0.629
	Middle-aged	0.739	0.068	0.028	0.484	0.128	0.721	0.760	0.844
	Young	0.705	0.133	0.003	0.477	0.530	0.345	0.530	0.310
Elderly vs middle-aged	N	0.002	0.019	0.006	0.077	0.011	0.010	0.014	0.126
	N+P	0.231	0.122	0.257	0.002	0.001	0.085	0.027	0.189
	F	0.272	0.007	0.072	0.023	0.246	0.011	0.003	0.516
	F+P	0.131	0.137	0.135	0.404	0.012	0.090	0.038	0.241
Elderly vs young	N	0.009	0.864	0.020	0.245	0.033	0.172	0.010	0.467
	N+P	0.673	0.434	0.783	0.221	0.010	0.334	0.462	0.001
	F	0.606	0.132	0.303	0.251	0.616	0.274	0.131	0.548
	F+P	0.127	0.739	0.315	0.747	0.016	0.575	0.228	0.009
Middle-aged vs young	N	0.485	0.046	0.367	0.261	0.874	0.318	0.525	0.650
	N+P	0.430	0.080	0.279	0.187	0.133	0.439	0.080	0.186
	F	0.638	0.189	0.782	0.191	0.700	0.511	0.376	0.755
	F+P	0.741	0.268	0.487	0.664	0.764	0.246	0.410	0.376

Shown are the p-values of the statistical tests. In the upper part of the table, the comparisons between the conditions are shown for all subjects together and for each group. In the lower part of the table, the comparisons between the groups are listed. Values highlighted in grey are significant ($p < 0.025$). Abbreviations: N = condition N (target two steps ahead); F = condition F (target four steps ahead); N+P = condition N+P (target two steps ahead, low foot clearance requested); F+P = condition F+P (target four steps ahead, low foot clearance requested)

Table 2.2: Head-movement and gaze behaviour parameters for each condition

Condition	Parameter	All subjects	Elderly	Middle-aged	Young
N	Pattern type	Number of subjects	Number of subjects	Number of subjects	Number of subjects
	1	8	5	1	2
	2	9	6	1	2
	3	22	2	10	10
	Amplitude [cm]				
	head	17 [0-29]	27 [11-36]	10 [0-16]	26 [0-36]
	gaze	6 [0-38]	36 [12–72]	4 [0–6]	6 [0–25]
	Latency [s]				
	head	0.81 [0.38-1.03]	0.39 [0.37-0.83]	1.03 [0.70-2.07]	0.86 [0.53-1.01]
	gaze	0.69 [0.33-1.04]	0.31 [0.25–0.65]	0.71 [0.70–1.20]	0.93 [0.42–1.12
	Duration [s]				
	head	0.44 [0.00-0.81]	0.75 [0.54-0.88]	0.28 [0.00-0.57]	0.44 [0.00-0.84]
	gaze	0.38 [0.00-0.82]	0.78 [0.54–1.02]	0.11 [0.00–0.45]	0.35 [0.00–0.65]
	Clearance [cm]	7 [5-9]	8 [6–9]	7 [4–8]	8 [4–9]
N+P	Pattern type	Number of subjects	Number of subjects	Number of subjects	Number of subjects
	1	22	9	5	8
	2	6	2	2	2
	3	12	3	5	4
	Amplitude [cm]				
	head	41 [21-67]	46 [28-55]	24 [14-45]	48 [26-116]
	gaze	61 [7-99]	73 [25–104]	28 [2–86]	64 [13–100]
	Latency [s]				
	head	0.54 [0.36-1.05]	0.44 [0.35-0.52]	1.24 [0.58-2.08]	0.56 [0.23-1.22]
	gaze	0.45 [0.33-0.99]	0.33 [0.27–0.44]	0.75 [0.50–1.83]	0.49 [0.37–1.27]
	Duration [s]				
	head	0.93 [0.48-1.11]	1.02 [0.78-1.13]	0.68 [0.38-1.03]	0.93 [0.44-1.08]
	gaze	0.89 [0.33-1.03]	1.00 [0.78–1.17]	0.48 [0.06–0.91]	0.97 [0.35–1.04]
	Clearance [cm]	4 [3-5]	5 [4–7]	4 [3–6]	3 [2–4]
F	Pattern type	Number of subjects	Number of subjects	Number of subjects	Number of subjects
	1	10	4	2	4
	2	13	6	4	3
	3	16	4	6	6
	Amplitude [cm]				
	head	38 [13-84]	59 [42-97]	22 [3-36]	37 [6-80]
	gaze	58 [1-159]	132 [10–172]	30 [0–121]	28 [0–167]
	Latency [s]				
	head	0.51 [0.32-1.10]	0.34 [0.26-0.54]	0.78 [0.57-1.71]	0.46 [0.34-1.07]
	gaze	0.47 [0.32-1.03]	0.41 [0.30–0.67]	0.62 [0.39–1.45]	0.60 [0.33–1.15]
	Duration [s]				
	head	0.53 [0.32-0.92]	0.82 [0.58-0.93]	0.39 [0.08-0.57]	0.45 [0.06-0.96]
	gaze	0.41 [0.08-0.97]	0.81 [0.43–1.11]	0.20 [0.00–0.31]	0.41 [0.00–0.97]
	Clearance [cm]	9 [6-10]	7 [5–9]	7 [6–10]	9 [6–10]
F+P	Pattern type	Number of subjects	Number of subjects	Number of subjects	Number of subjects
	1	21	11	5	5
	2	13	3	3	7
	3	8	2	4	2
	Amplitude [cm]				
	head	79 [30-120]	86 [64-113]	39 [5-123]	80 [29-141]
	gaze	155 [37-198]	176 [119–240]	80 [3–185]	107 [34–201]
	Latency [s]				
	head	0.42 [0.32-0.98]	0.38 [0.30-0.53]	0.76 [0.33-1.33]	0.45 [0.31-1.07]
	gaze	0.50 [0.29-0.81]	0.28 [0.23–0.51]	0.57 [0.48–1.08]	0.66 [0.39–1.19]
	Duration [s]				
	head	0.94 [0.58-1.13]	1.00 [0.73-1.14]	0.73 [0.14-0.95]	0.95 [0.54-1.15]
	gaze	0.87 [0.30-1.11]	0.93 [0.77–1.35]	0.51 [0.20–0.83]	0.83 [0.20–1.06]
	Clearance [cm]	5 [3-6]	5 [4–7]	4 [3–6]	4 [3–5]

Except for the gaze-pattern types, where the number of subjects is presented, all other values are median values and inter-quartile ranges (between brackets). The results are listed for all subjects together and for each group separately. Abbreviations: N = condition N (target two steps ahead); F = condition F (target four steps ahead); N+P = condition N+P (target two steps ahead, low foot clearance requested); F+P = condition F+P (target four steps ahead, low foot clearance requested); Pattern 1 - gaze-turn on the obstacles; Pattern 2 - gaze-turn into the direction of the obstacles; Pattern 3 - no gaze-turn to the obstacles.

2.5 Discussion

The present study investigated differences in gaze behaviour between healthy elderly, middle-aged and young subjects during stepping over obstacles. In short, we found that (i) compared to the younger subjects, more elderly turned their gaze on or into the direction of the obstacles in the near target condition, (ii) the elderly turned their gaze earlier and for a longer time on or into the direction of the obstacles (except for condition F), (iii) in the high-precision conditions, more subjects turned their gaze on or into the direction of the obstacles with a larger gaze-amplitude and for a longer time compared to the unrestricted conditions. This result was only partly confirmed in the subgroups.

2.5.1 Modified gaze behaviour

Compared to middle-aged and young subjects, more elderly turned their gaze downwards to the obstacles in condition N with the visual-fixation point two steps ahead. Indeed, peripheral vision proved to be sufficient for safely avoiding a suddenly occurring obstacle in young subjects who looked at a target about two steps ahead (Marigold et al., 2007). In the similar condition in the present study, the young and middle-aged subjects were able to get the necessary visual inputs from the peripheral vision, unlike the elderly. This might be explained by the fact that peripheral visual acuity deteriorates with age (Meisami et al., 2007; Sekuler et al., 2000).

Apart from condition F with the target four steps ahead, the elderly turned their gaze earlier and for a longer time to the obstacles. Apparently, the elderly required prolonged visual sampling to obtain the necessary information, which is in line with literature (Chapman and Hollands, 2006; Patla, 1998) and is also observed during walking over more difficult terrains (Patla et al., 1996). Elderly people rely more on visual information probably due to a reduced proprioceptive or a vestibular control (van Hedel and Dietz, 2004; Wolfson et al., 1992).

2.5.2 Modified locomotor performance

The elderly did not reduce the foot clearance in the high-precision conditions as much as young subjects. Perhaps the elderly could use the visual information less than young

subjects, as the elderly might have more difficulty in visually following the moving obstacle due to impaired visual tracking ability (Paquette and Fung, 2011) or due to limited response-time for optimizing the walking trajectory (Weerdesteyn et al., 2005b).
Another interesting observation was that over all subjects, the clearance in condition N was smaller than in condition F, even when no low obstacle-crossing was requested. Apparently, a better availability of peripheral vision might allow a more economic stepping over the obstacles by decreasing the vertical foot clearance, which is in line with a previous study (Patla, 1998). Again, the deterioration of the peripheral acuity in age might explain why this was not found in the elderly subjects.

2.5.3 Head-movements

Head-movements showed more or less similar characteristics as gaze-movements, indicating that the eye- and head-movements changed congruently. However, in gaze-pattern 3 with no gaze-turn to the obstacle, more than half of the subjects showed a head-movement downwards without a gaze-turn downwards, as previously reported (Marigold et al., 2007).

2.5.4 Limitations

In our study, we analysed gaze behaviour during repetitively stepping over a randomly released obstacle under equal temporal conditions. This enabled a relative accurate assessment of gaze behaviour and stepping performance for this specific movement. However, this approach limits information about the gaze behaviour at (slightly) earlier or later released obstacles as, for example, investigated by Marigold et al. (2007). Furthermore, the relevance for daily life of an obstacle avoidance task on a treadmill can be questioned compared to over-ground walking. However, this approach enabled us to study gaze behaviour in a repeatable, yet unexpected, way. Indeed, unexpected trips over suddenly approaching obstacles occur frequently, as the annual estimate of tripping over a cat or dog approximate 24’000 cases in the USA (Stevens et al., 2010).

2.6 Summary and conclusions

The results have highlighted different gaze behaviour strategies during walking over obstacles in healthy well-performing elderly subjects, who did not report any falls.

Elderly subjects looked earlier and prolonged at the obstacles than younger subjects. Additionally, in the condition with a near target for visual fixation in-between two triggered obstacles, more elderly subjects used their visual input and turned the gaze downwards to the obstacles compared to the younger ones, who might have better used peripheral vision. Differences were found not only between elderly and young subjects but also between elderly and middle-aged subjects. The hypotheses that the elderly depend more on visual input was confirmed.

3 Gaze behaviour during obstacle avoidance in patients with an incomplete spinal cord injury[1]

Authors: Sandra Keller Chandra, Stephanie Eva Müller, Hubertus J.A. van Hedel

3.1 Abstract

Background: Patients with an incomplete spinal cord injury (iSCI) have a higher risk of falling. An impairment of the somatosensory system may be compensated by adaptations in gaze behaviour. *Issue*: We investigated gaze behaviour in iSCI-patients while they stepped over obstacles on a treadmill. *Method:* Eleven iSCI-patients and eleven age- and gender-matched healthy subjects walked on a treadmill and stepped over a repetitively approaching obstacle announced by an acoustic warning signal. Gaze- and head-movements were measured by video-oculography. In between two obstacle-steps, subjects visually fixated a target located four steps ahead on the floor. After the warning signal, they were free to look anywhere. Subjects had to perform a normal trial, a high-precision motor-task trial and a dual-task trial. *Results*: In the high-precision condition, iSCI-patients turned their gaze significantly later to the obstacle compared to the healthy subjects. Compared to the normal condition, the healthy subjects adapted in the high-precision condition many gaze behavioural parameters (e.g. more subjects turned their gaze to the obstacle and the gaze was turned earlier and longer towards the obstacle) and improved obstacle task performance. There were no changes in gaze behaviour and obstacle avoidance task performance between the normal and double-task condition.
Conclusion: Under high constraints, patients with an iSCI showed less flexible gaze behaviour, which might contribute to a higher risk of falling.

3.2 Introduction

Safe locomotion is essential in daily life. Even for healthy subjects it may be difficult to maintain balance and ambulate safely in conditions with poor sensory input as, for

[1] This manuscript has been submitted to Spinal Cord. Measurements were conducted by Stephanie Eva Müller (master student) with support by Sandra Keller Chandra. Analyses were conducted by Stephanie Eva Müller and Sandra Keller Chandra. The manuscript was written by Sandra Keller Chandra and revised by the co-authors.

instance, reduced vision in the darkness or slippery terrain. Such situations are evidently even more challenging for patients suffering from a sensorimotor lesion. Although a high percentage of incomplete spinal cord injured (iSCI) patients are able to regain walking ability (Dobkin et al., 2006), studies report 60 - 75 % falls in iSCI-patients (Brotherton et al., 2007; Wirz et al., 2010). Walking over uneven terrains or negotiating curbs and doorsteps may cause them to fall (David and Freedman, 1990). Distraction too, such as simultaneously having a conversation or paying attention to the traffic, may be an additional challenge to iSCI-patients (Lajoie et al., 1999).

Postural control and safe locomotion require sensory inputs from the visual, vestibular, and somatosensory systems. In iSCI-patients, impairments of the somatosensory pathways and/or of the vestibulospinal tracts may lead to compensatory mechanisms, especially under difficult conditions (Liechti et al., 2008). A common compensatory strategy is to increase the dependency on vision (van Hedel et al., 2005). However, although it is reasonable to assume that patients with an iSCI depend more on their visual input, we are unaware of studies that investigated gaze behaviour of these patients during a locomotor task.

In this study, we investigated the gaze behaviour of iSCI-patients while they stepped over obstacles and compared their performance to that of healthy subjects. A relatively simple obstacle avoidance task, a high-precision motor task and a cognitive dual-task simulated demanding daily life conditions. We hypothesised that, compared to age-matched healthy subjects, the iSCI-patients would fixate their gaze on the moving obstacle earlier and for a longer period in order to be able to avoid it safely. Furthermore, we hypothesised that, in the more challenging high-precision task and cognitive dual-task conditions, the visual dependency might increase even more and task performance be observed to decrease, especially in the iSCI-patients.

3.3 Methods

3.3.1 Subjects

The study was approved by the Cantonal Ethics Committee Zurich. Participants gave written agreement prior to data collection. Eleven iSCI-patients (mean ± SD, 43.6 ± 11.6 years; Table 3.1) and eleven healthy gender and aged-matched subjects

(43.3 ± 11.6 years) participated. Patients were recruited from the database of the SCI Center Balgrist, Zurich. Inclusion criteria were (i) chronic (> 12 months), (ii) incomplete para- or tetraplegia ASIA (American Spinal Injury Association) Impairment Scale D (ASIA, 2002), (iii) ability to walk without aids or personal assistance (revised Walking Index of Spinal Cord Injury, WISCI II score of 20 (Ditunno and Dittuno, 2001), and (iv) age between 20 and 65 years. Only subjects without short-sightedness or with the possibility to wear contact lenses were recruited, as glasses could not be worn for video-oculographic investigation.

Table 3.1: Characteristics of patients with incomplete spinal cord injury

Subject	Gender	Age [years]	Duration of lesion [years]	Level of lesion	Aetiology	Vibration Threshold values	ASIA motor score	ASIA light touch score	Tibialis SSEP P-40 Latency [ms]
1	f	33	2	Tetra sub C4	tumour	0	100	74	no potential
2	m	43	1	Tetra sub C3	traumatic	72	96	68	left: 40.9 right: 43.1
3	m	58	19	Para sub Th11	traumatic	46	92	92	not tested
4	f	25	1	Para sub L3	traumatic	40	100	107	left: 44,5 right: 43,1
5	f	45	14	Para sub Th12	traumatic	63	not tested	not tested	not tested
6	m	63	3	Para sub Th12	tumour	18	94	88	left: 45,9 right: no potential
7	m	37	7	Tetra sub C5	traumatic	28	95	57	left: 58.7 right: 59.3
8	f	40	8	Para sub Th12	traumatic	64	98	101	left: 41 right: 41
9	m	50	1	Para sub L1	tumour	28	98	102	left: no potential right: no potential
10	m	53	7	Para sub Th12	tumour	56	98	107	left: 45 right: 48.7
11	m	33	3	Tetra sub C6	traumatic	58	91	94	left: 40.9 right: 43.1

Abbreviations: f: female, m: male; Para: paraplegia, Tetra: tetraplegia, C: cervical, Th: thoracic; Maximal vibration threshold is 80, calculated by the sum of 10 measurement points (values between 0 and 8), normal values: age ≤ 40 → values ≥ 45 / age 41-60 → values ≥ 40 / age 61-85 → values ≥ 35 (Martina et al., 1998); ASIA: American Spinal Injury Association, the maximal ASIA motor score is 100, the maximal ASIA light touch score is 112; SSEP P-40: somatosensory evoked potentials P-40, normal value: 41.4 ms (Jörg, 1993)

3.3.2 Data collection

Treadmill with obstacle machines

Subjects walked on a split-belt treadmill (Woodway, Weil am Rhein, Germany) with two obstacle-machines (ALEA Solutions, Zurich, Switzerland) to study repetitive stepping over a right and a left foam stick, 18 cm above floor (Erni and Dietz, 2001). Force sensors (Kistler, Winterthur, Switzerland) under the treadmill detected the right and left heel strike, which randomly triggered the start of the right or left obstacle, respectively, for stepping over into the next step-cycle. The delay between obstacles was randomised between 13 and 25 seconds. The triggered obstacle, announced by an acoustic warning signal, moved with the same speed as the treadmill, folded up at the end of the treadmill, and moved back into the starting position about 70 cm in front of the subject (Fig. 3.1). Touched obstacles either folded back or were released. The vertical distance between the crossing leading foot and the obstacle (i.e. foot clearance) was measured by infrared sensors attached to the obstacle machines. In the high-precision conditions (see paragraph 3.3.3) corresponding acoustic feedback tones of different frequencies were given to the subjects defining six levels in 2 cm intervals between 0 cm and 12 cm.

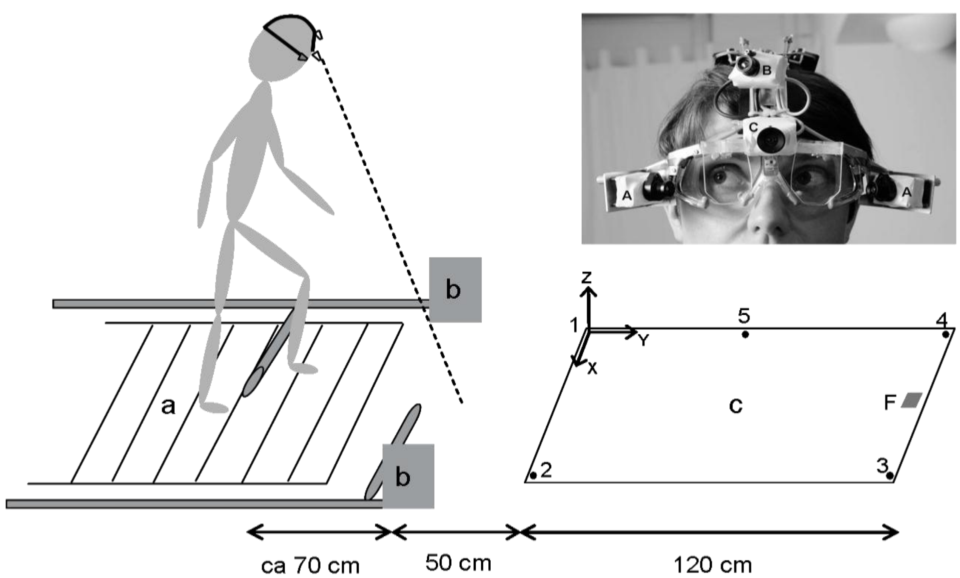

Figure 3.1: Experimental setup and eye-tracking system. (a) treadmill, (b) obstacle machines and (c) floor plate. 1 - 5 = LEDs spanning a coordinate system with the origin at LED 1, F is the target for gaze fixation during the interval between two triggered obstacles. Video-Oculograph (EyeSeeCam, Munich, Germany) with two eye-cameras (A), a gaze-driven head-camera (B) and an infrared-sensitive scene-camera (C)

Eye tracking system

A video-oculograph (VOG; EyeSeeCam, Munich, Germany) with an additional gaze-driven head-camera and an infrared-sensitive scene-camera was used for measuring gaze- and head-movements (Schneider et al., 2005). Eye-movements were recorded via two transparent mirrors by two eye-cameras (recording-frequency 76 Hz) laterally attached to the frame of the goggles (Fig. 3.1). The gaze-driven head-camera (recording-frequency 30.4 Hz) was aligned parallel to the eyes by servo drivers continually updated based on the eye-movement data. The infrared-sensitive scene-camera (recording-frequency 76 Hz) was used to detect head-movements.

Experimental setup

A floor plate in front of the treadmill was equipped with five infrared LEDs lying in an x-y-plane (Fig. 3.1). The LEDs were invisible to the human eye, but could be detected by the infrared-sensitive scene-camera. By knowing the position of the plane in relation to the environment and by combining the data of eye- and head-movements, the gaze fixation points (gaze-on-plane) and the positions to which the head pointed (head-on-plane) could be determined.

3.3.3 Protocol

Preliminarily, subjects answered a questionnaire about their health and incidence of fall. As an indicator of proprioceptive perception, five vibration thresholds (os metatarsale, malleolus medialis, tuberosita tibiae, caput fibula, crista iliaca) on the left and right side were measured three times in a supine position with a graduated Rydel-Seiffer tuning fork C 128 Hz (Martina et al., 1998). Medians of the three measurements of each anatomical location were summed resulting in a sum-score between 0 (no vibration perception) to 40.

Baseline values were determined by subjects carrying out a 2 back-task of 150 seconds in a sitting position. Every two seconds, one of eight letters (A-E-I-L-M-O-S-V) sounded in a randomised order. If a letter was the same as two letters before, participants had to repeat it loudly. This trial was recorded on video for analysis.

Subjects were familiarized with walking on the treadmill and stepping over the obstacles. They could be secured by a ceiling-mounted harness. Walking position on the treadmill was defined to enable subjects to step over the obstacle without changing their step-rhythm. Walking speed was 2.5 km/h. After VOG-calibration, subjects had to pass four conditions with 20 obstacles each. In condition N (normal), subjects were instructed in-between obstacle-steps to gaze at a 2 x 3 cm fixation point F located about four steps in front of them on the floor plate (Fig. 3.1). As soon as the obstacle was triggered and the acoustic warning signal sounded, subjects were free to let their gaze roam. Condition H (high-precision condition) was the same as condition N with the additional instruction to step over the obstacle with minimal vertical foot clearance. Subjects received an acoustic feedback about their performance. Condition D (dual-task) was the same as condition N, but with the addition of the cognitive 2-back-task. Again, the cognitive 2 back-task was recorded on video for evaluation. The fourth condition was the same as condition N but with a visual fixation point only two steps ahead. This condition was not analysed for the current study. Subjects started either with this fourth condition or with the condition N; the order of the other three conditions was randomised. Before and after each condition, subjects had to define their subjective physical exhaustion based on a Borg-scale (6-20) (Borg, 1998).

3.3.4 Data analysis

Artefacts and winks were eliminated from the raw-data by a 5 Hz median filter. For each subject and each condition, the median gaze-on-plane was calculated 1.3 s before and 3.9 s after the obstacle-trigger over all 20 obstacle steps for the right and left leg separately. The left and right median gaze-on-plane trajectories were then averaged. The same analysis was performed for the head-on-plane data. Several gaze-characteristics were derived from the sagittal data (Fig. 3.2): (i) the amplitude of downwards gaze- and head-movement (gaze-amplitude, head-amplitude), (ii) the time between the obstacle-trigger and the onset of downwards gaze- and head-movement (gaze-latency, head-latency), and (iii) the duration between the onset of downwards gaze- and head-movement and redirection upwards (gaze-duration, head-duration). To minimise subjectivity in determining these events, the analyses were performed twice by the same investigator on different days and once by another investigator. The median value of these three analyses was used.

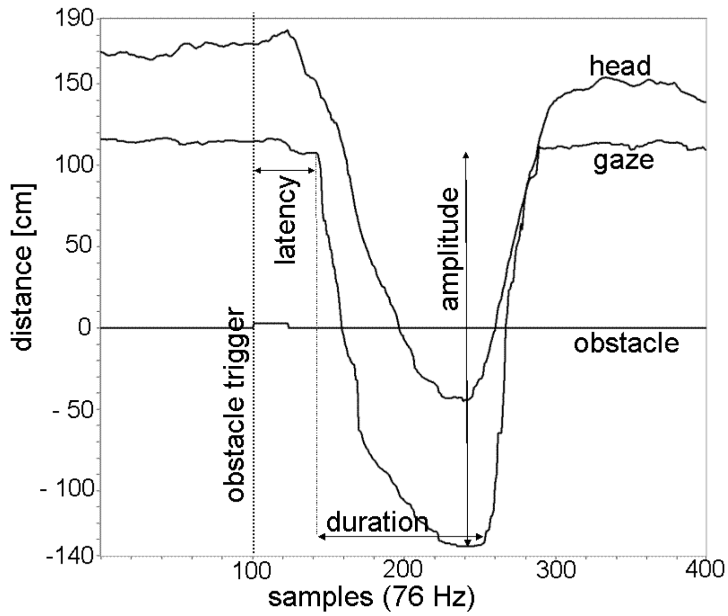

Figure 3.2: An example of head-on-plane and gaze-on-plane in relation to the obstacle trigger together with the analyzed parameters amplitude, latency and duration of gaze- and head-movements. The plots are averaged left and right medians of all obstacle steps in one subject in a single condition. The upper trajectory shows the head-on-plane [cm], the lower trajectory gaze-on-plane [cm].

On the basis of the gaze-amplitudes, three gaze-patterns were defined: Pattern 1 – the gaze was directed at the obstacle (amplitude ≥ 155 cm); Pattern 2 – the gaze was directed towards the obstacle, but not completely (amplitude between the defined limits of gaze-pattern 1 and 3); and Pattern 3 - the gaze was not turned away from the target (amplitude ≤ 15 cm). These borders were determined on the basis of 66 defined control measurements. Gaze-pattern 2 was additionally verified by studying the gaze-driven video images and the examination of the gaze-on-plane data for each individual obstacle step, before calculating the median. If no downwards gaze- or head-movement was observed, the amplitude and duration were set to 0 cm and 0 s, respectively, while the latency was defined as a missing value. Gaze- or head-movements that occurred later than two seconds after the obstacle-trigger were not considered.

In the auditory 2-back-task, a missed or false uttered letter was counted as a mistake and subtracted from all possible correct answers. The cognitive performance was defined by dividing correct answers by the total number of correct possibilities and expressed as a percentage. The performance of the 2-back-task during obstacle stepping was compared to the performance of the baseline recorded after the vibration threshold measurements.

The three gaze-patterns were treated as ordinal data. The Mann-Whitney-U Test was used for the pair-wise comparison between the two groups, (significance-level $p < 0.05$; tendency $p < 0.1$). We used the Wilcoxon Test for the pair-wise comparisons between the conditions N & H and N & D, and performed Bonferroni's adjustment (significance-level $p < 0.025$; tendency $p < 0.05$).

3.4 Results

Subjects showed no physical exhaustion during the tasks (Borg-scale scores ≤ 8, in three patients ≤ 12). Vibration thresholds were poorer for patients than for healthy subjects (Table 3.1). No healthy subject reported more than one fall in the preceding three months. Three iSCI-patients had more than one fall in daily life in the preceding four weeks, and four patients in the preceding three months. The sum of falls in all patients was ten in the four weeks preceding the study, and 31 in the preceding three months (one person reported eight falls every month).

3.4.1 Inter group comparison

In condition N, iSCI-patients showed a tendency for a prolonged head-latency (Fig. 3.3b) and for dropping more obstacles compared to healthy subjects (Table 3.2). In condition H, healthy subjects showed a tendency for a longer head-duration (Fig. 3.3c), while iSCI-patients turned their gaze significantly later to the obstacle (Fig. 3.3e). In condition D, healthy subjects tended to step higher over the obstacle, while iSCI-patients tended to drop more obstacles (Table 3.2). There was no difference between the groups in the cognitive dual-task performance. However, during the baseline assessment, iSCI-patients tended to perform the 2-back-task less well than healthy subjects (Fig. 3.4).

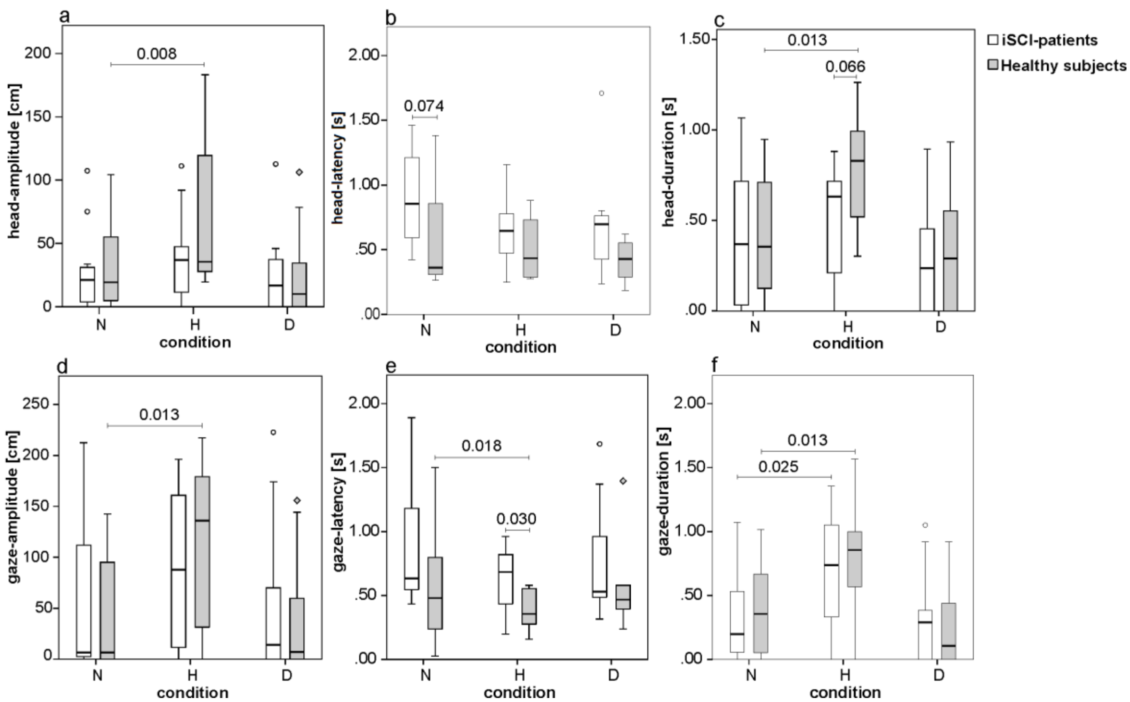

Figure 3.3: Box plots of a) head-amplitude, b) head-latency, c) head-duration, d) gaze-amplitude, e) gaze-latency, and f) gaze-duration. White box plots are for iSCI-patients, grey box plots for healthy subjects; N = normal condition, H = high-precision condition, D = dual-task condition; number above lines indicate p-values

Table 3.2: Foot clearance, number of touched and dropped obstacles

	Condition N			Condition H			Condition D		
	iSCI	Healthy	P-value	iSCI	Healthy	P-value	iSCI	Healthy	P-value
Foot-clearance [cm]	6 [4-8]	7 [6-7]	0.341	4 [4-6]	4 [3-5]	0.718	6 [5-7]	7 [7-9]	0.082
Touched (number)	13	7	0.564	20	17	0.707	9	10	0.885
Dropped (number)	5	0	0.069	12	11	0.890	4	0	0.069

Presented are median and interquartile range (in brackets) of foot-clearance, the sum of touched and dropped obstacles over all subjects of each group and the p-values of the inter-group comparison. Abbreviations: N = normal condition; H = high-precision condition; D = dual-task condition; iSCI = incomplete spinal cord injury.

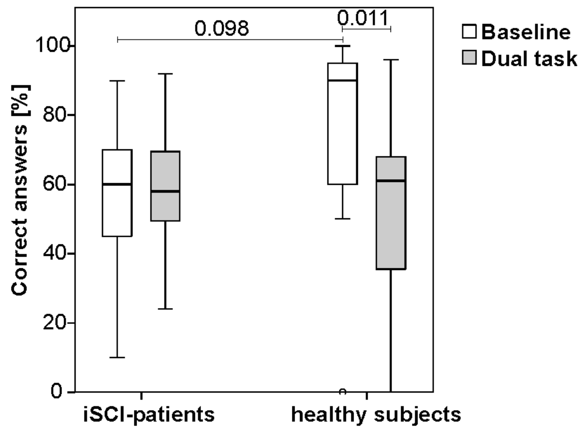

Figure 3.4: Cognitive performance of the baseline (white box plots) and the dual task condition (grey box plots). Number above lines indicate p-values

3.4.2 Inter condition comparison

Normal versus high-precision condition

The iSCI-patients tended to gaze longer to the obstacle in condition H than in N (Fig. 3.3f). More differences were observed for the healthy subjects: In condition H, head- and gaze-amplitudes were larger, head-duration was elongated, and they turned their gaze downwards earlier and longer (Fig. 3.3a, c-f). Overall, more healthy subjects turned their gaze to the obstacle in condition H than in condition N (Fig. 3.5). Additionally, median foot clearance was smaller in this group ($p = 0.003$) and the sum of dropped obstacles was larger ($p = 0.016$, see Table 3.2).

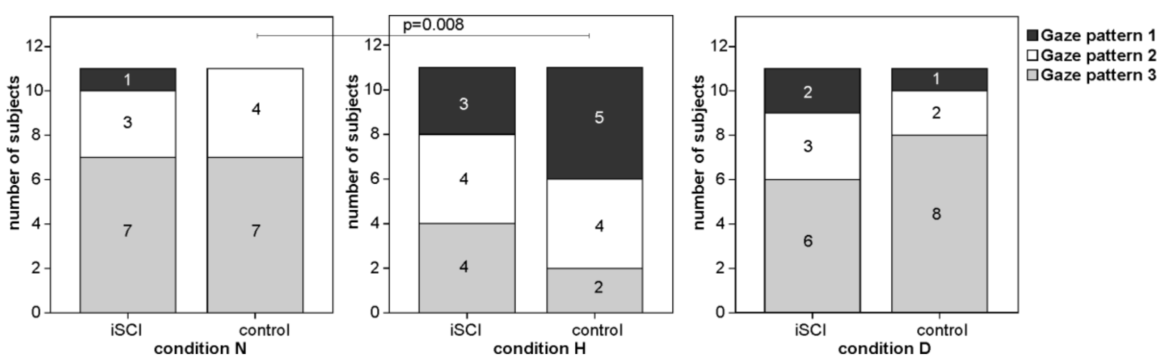

Figure 3.5: Gaze-pattern for the normal condition N, high precision condition H, and dual-task condition D. Values in the bars are the number of subjects in that gaze pattern; gaze pattern 1 = gaze-turn to the obstacle, gaze pattern 2 = gaze-turn into the direction of the obstacle, gaze pattern 3 = no gaze-turn to the obstacle

Normal versus dual-task condition

There were no differences between condition N and D in gaze behaviour and motor performance for both groups. Healthy subjects showed a significant worse cognitive performance in the dual-task condition compared to the baseline (Fig. 3.4).

3.5 Discussion

In this study, we focused on the gaze behaviour of iSCI-patients stepping over obstacles in a normal, a high-precision and a dual-task condition. In the high-precision condition, iSCI-patients turned their gaze later towards the obstacles compared to healthy subjects. We assume that the iSCI-patients visually fixated the stable target longer to improve balance. Indeed, such a compensatory strategy has been reported repeatedly in healthy subjects (Edwards, 1946; Paulus et al., 1984).

In the high-precision condition, gaze behaviour and task performance in the healthy control subjects adapted as expected. The reduction in foot clearance was accompanied by an increase in visual input (more, earlier and longer gaze-turns to the obstacles with larger gaze- and head-amplitudes). This is in line with studies showing that walking on demanding path-ways requires increased visual sampling (Patla et al., 1996). The iSCI-patients, however, were not able to decrease foot clearance in this condition and showed no change in gaze behaviour. In a previous study (van Hedel et al., 2005), iSCI-patients were able to minimize foot clearance, but at a slower rate than healthy subjects and only when visual input from the treadmill and the obstacle was available. We assume that the lack of improvement in motor performance in the present study might have been caused on the one hand by the smaller number of obstacle steps in this condition and, on the other, because patients were able to use the given target to stabilise their posture and did not therefore gaze towards the obstacle as needed for an improvement of foot clearance.

If two simultaneously performed tasks exceed the capacity of the cognitive system, the performance of one or both tasks will be affected (Hausdorff et al., 2008). In the dual-task condition, changed gaze behaviour was detected neither in iSCI-patients nor in the healthy controls. However, iSCI-patients tended to step with less foot clearance over the obstacle and dropped the obstacles more frequently than the healthy subjects, which could be considered a riskier behaviour. Indeed, in real life, obstacle-touches might result in a fall.

Only the healthy subjects performed the cognitive task significantly worse during the obstacle avoidance task compared to the baseline. Apparently, healthy subjects prioritized the performance of the motor task for safe locomotion above the cognitive task. Patients with an iSCI did not show any differences in the cognitive performance between the dual-task and the baseline conditions. However, at baseline, their cognitive performance tended to be worse than that of the healthy subjects. This poorer cognitive performance of iSCI-patients might be explained by a reduced trunk control, which increased the cognitive demand to sit, higher excitement of the iSCI-patients or a higher ambition of the healthy subjects to perform well on the cognitive task. Anyway, the low baseline performance of the patients and the huge variability between the patients may be a reason for the lack of difference in this group between the baseline and the dual-task performance.

3.6 Conclusions

Contrary to our expectation, in the normal condition, iSCI-patients gazed not longer at the obstacle compared to healthy subjects, but tended to focus longer on the stabilising visual target, which we interpreted as a compensatory strategy to increase balance support. In contrast to iSCI-patients, healthy subjects fixated earlier and prolonged on the obstacle during a high-precision condition compared to the normal condition and were able to optimize their task performance. The dual-task condition showed that, even for healthy subjects, the obstacle avoidance task was demanding, as their cognitive performance became worse compared to the baseline. The iSCI-patients showed already a poor baseline cognitive performance and, consequently, did not deteriorate when simultaneously stepping over the obstacle. Overall, iSCI-patients seemed to show a less flexible motor performance and gaze behaviour compared to healthy subjects.

4 Gaze behaviour during obstacle avoidance in patients with a unilateral vestibular loss[1]

Authors: Sandra Keller Chandra, Christopher J. Bockisch, Volker Dietz, Stefan C.A. Hegemann, Dominik Straumann, Hubertus J.A. van Hedel

4.1 Abstract

Background: Locomotor control adapt to external demands by using input from proprioceptive, vestibular, and visual systems. An impairment of one of these inputs has to be compensated by the intact sensory systems, behaviour will change or the risk of falling may increase. *Issue*: We investigated gaze behaviour in patients with unilateral vestibular loss during walking on a treadmill and stepping over obstacles. *Method:* Patients with a unilateral complete vestibular loss were compared with a group of age- and gender-matched healthy subjects. Subjects walked on a treadmill and stepped over a repetitively approaching obstacle (right or left side) announced by an acoustic warning signal. Gaze- and head-movements were measured by video-oculography. During the time between two obstacle-steps, subjects visually fixated a target located two or four steps ahead on the floor. After the warning signal, subjects were free to look anywhere. *Results*: No significant differences in gaze behaviour and locomotor performance between the patient and the control groups were observed. *Conclusion:* The unilateral vestibular loss was well compensated in this precise locomotor task. Patients did not change their gaze behaviour for successful obstacle avoidance. We conclude that central compensation of unilateral vestibular hypofunction is effective to enable normal precision locomotion in patients.

4.2 Introduction

Safe locomotion requires a complex interaction between motor and sensory systems. Proprioceptive, vestibular and visual inputs are required for correct motor output. If one

[1] This manuscript has been submitted to Human Movement Science. All measurements and analyses were conducted by Sandra Keller Chandra. The manuscript was written by Sandra Keller Chandra and revised by the co-authors.

of these inputs is diminished or lost, as, for example, in patients with a vestibular disease, the risk of falling is increased (Pothula et al., 2004; Whitney et al., 2000).

The vestibular system provides input concerning the orientation of the head and balance. However, balance is also influenced by visual input. Several studies show that postural stability, quantified by measuring the postural sway during standing on a force-platform, is increased during visual fixation of a stable target, but decreased when the eyes were closed (Edwards, 1946) or visual acuity became reduced (Paulus et al., 1984). Glasauer et al. (2005) showed that not only moving images on the retina (retinal flow), but also eye-movements increase body sway.

Vision also influences head-movements: In healthy subjects, the head is more stabilised while visually fixating a target than under conditions with closed eyes (Cappa et al., 2008). Even the imagination by itself to gaze at a stable target with closed eyes reduces head motion (Cappa et al., 2008). Standing on an oscillating platform, the head is almost completely stable under good visual conditions. However, as visual acuity decreases, the more the head moves along with the platform (Schmid et al., 2008).

Head-movements in turn influence postural sway. In a study of Fukushima et al. (2008), subjects had to follow with a laser mounted on a helmet a moving target. Their postural sway was significantly larger than during following the moving target only with their eyes while keeping the head stable.

During locomotion, visual input appears to be more dominant than vestibular input, as shown in a study with healthy subjects (Kennedy et al., 2003). When walking straight ahead, a visual disturbance induced by wearing goggles with a prism was stronger (i.e. subjects deviated from the path in the direction of the visual input by the prism) than a vestibular disturbance caused by galvanic vestibular stimulation (Kennedy et al., 2003).

In subjects with vestibular disorders, the visual system becomes even more important for posture control and overtakes parts of the diminished or lost vestibular functions (Redfern et al., 2001). Nashner et al. (1982) showed that, in situations with inadequate visual inputs, the postural sway of patients with a greater vestibular loss was larger compared to that of less affected vestibular patients. During locomotion with closed eyes, vestibular patients walked slower and deviated earlier and more from a straight path than healthy subjects (Borel et al., 2004; Cohen, 2000).

However, after a unilateral vestibular neurotomy, patients seem to cope well. One month after surgery, normal walking speed was better than before surgery and became comparable to the walking speed of healthy subjects, both in the conditions with eyes open and eyes closed. Additionally, after recovery time of one month, gait deviation from a straight path was the same as in healthy subjects when walking at normal and fast speeds as long as the eyes were open (Borel et al., 2004). Even in challenging daily life, it appears that patients with a unilateral vestibular loss can compensate well, as the incidence of falls in patients with a unilateral vestibular loss (mean age 63.0 ± 14.8 years) does not differ from that in healthy people aged over 65 years (Herdman et al., 2000).

We asked if this good rehabilitation in daily life, despite reduced vestibular function, might be due to a compensatory visual or motor strategy. Therefore, we investigated gaze behaviour in vestibular patients with a complete unilateral loss and compared it with healthy subjects during walking on a treadmill with obstacle avoidance. We hypothesised that patients with a complete unilateral vestibular loss will show a different gaze behaviour compared to the healthy subjects. Either these patients need more visual input, and therefore they would turn their gaze more to the obstacle, or they try to reduce head-movements and visually fixate a stable target in front of them for increased postural stability.

4.3 Methods

4.3.1 Subjects included in the study

The experiment was approved by the Zurich Cantonal Ethic Commission and has been performed in accordance with the ethical standards of the Declaration of Helsinki. The participants gave written agreement prior to data collection. Fourteen patients (nine men, five women, aged 37 - 67 years, mean 53 years) with a complete unilateral vestibular loss (four on the left side, ten on the right side) were recruited at the University Hospital Zurich. Twelve patients had a complete unilateral loss due to a labyrinthectomy or neurectomy, two patients showed a VOR-gain smaller than 0.3 (head-impulse-test) with unknown cause and were classified as complete unilateral vestibular loss (Halmagyi et al., 1990). The disease of all patients was chronic (time since surgery (for the two subjects without surgery from onset of treatment) 5 - 48 months, mean 21 months). The healthy control group was age and gender-matched (nine men, five female, aged 39 - 67 years, mean 53 years), without vestibular or other health problems. Only subjects without short-sightedness or with the possibility to wear contact lenses were recruited, as glasses could not be worn under the video-oculograph.

4.3.2 Data collection

Obstacle avoidance experiment

Subjects walked on a split-belt treadmill (Woodway, Weil am Rhein, Germany) with two obstacle-machines (ALEA Solutions, Zurich, Switzerland) to study repetitive stepping over a right and a left foam stick, 18 cm above floor (Erni and Dietz, 2001). Force sensors (Kistler, Winterthur, Switzerland) under the treadmill detected the right and left heel strike, which randomly triggered the start of the right or left obstacle, respectively. The time between obstacles was randomised between 13 and 30 seconds. The triggered obstacle moved with the same speed as the treadmill (2.5 km/h), folded up at the end of the treadmill, and moved back into the starting position about 70 cm in front of the subject (Fig. 4.1). The obstacles folded back or were released when subjects touched them. At the time of obstacle-release, the subjects heard a short acoustic warning signal. The vertical distance between the crossing leading foot and the obstacle (i.e. foot clearance) was measured by infrared sensors attached to the obstacle machines. In the high-precision conditions (see protocol 4.3.3), corresponding acoustic feedback tones of different frequencies were given to the subjects defining six levels in 2 cm intervals between 0 cm and 12 cm.

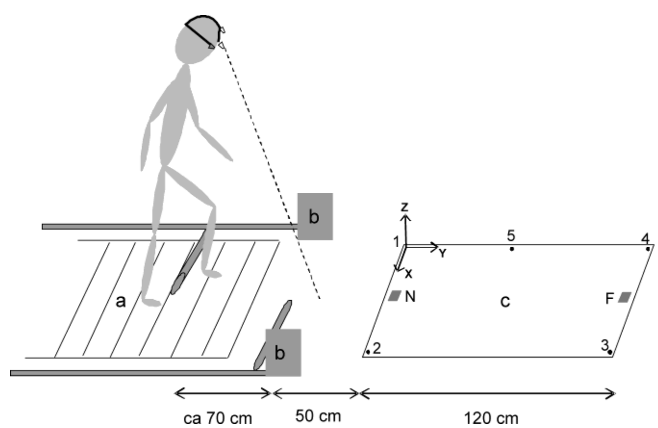

Figure 4.1: Experimental setup (a) treadmill, (b) obstacle machines and (c) floor plate. 1 - 5 = LEDs spanning a coordinate system with the origin at LED 1, N and F are the targets for gaze fixation in the different conditions

Eye tracking system

A video-oculograph (VOG; EyeSeeCam, Munich, Germany) with an additional gaze-driven head-camera and an infrared-sensitive scene-camera was used for measuring gaze- and head-movements (Schneider et al., 2005). Eye-movements were recorded by two eye-cameras (recording-frequency 76 Hz) laterally attached to the frame of the goggles without restricting the subject's view (Fig. 4.2). These cameras recorded movements of the pupils via two transparent mirrors. The gaze-driven head-camera (recording-frequency 30.4 Hz) was aligned parallel to the eyes by servo drivers continually updated based on the eye-movement data. The infrared-sensitive scene-camera (recording-frequency 76 Hz) was used for the head-movements (see setup below).

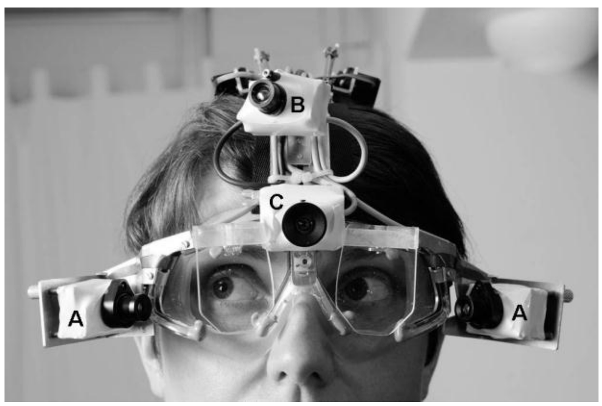

Figure 4.2: Video-Oculograph (EyeSeeCam, Munich, Germany) with two eye-cameras (A), a gaze-driven head-camera (B) and an infrared-sensitive scene-camera (C)

Experimental Setup

A floor plate in front of the treadmill was equipped with five infrared LEDs lying in a plane (Fig. 4.1). The LEDs were invisible to human eyes but could be detected by the infrared-sensitive scene-camera. By knowing the position of the plane in relation to the environment and by combining the data of eye- and head-movements, the gaze fixation points (= gaze-on-plane) and the positions where the head pointed at (= head-on-plane) could be determined even outside the floor plate.

Variables

Recorded and analysed were the vertical forces on the treadmill for detecting heel strike and toe-off, the obstacle trigger signals, foot clearance, gaze-on-plane, head-on-plane, and the video from the gaze-driven head-camera.

4.3.3 Protocol

Prior to the experiment, subjects were familiarized with walking on the treadmill and stepping over the obstacles. If necessary, subjects could be secured by a harness mounted on the ceiling, which was attached to the subjects loose enough to not influence task performance. The walking position on the treadmill was determined depending on the individual step length in such a way that subjects were able to step over the obstacle without changing their step-rhythm.

After the VOG was calibrated, subjects had to pass four conditions with 20 obstacles each. In-between obstacle-steps, subjects were instructed to gaze at a 2 x 3 cm fixation point located on the floor plate. As soon as the obstacle was triggered and the acoustic warning signal sounded, subjects were free to look wherever they wanted. In condition N (near), subjects had to look at the near target during the time in-between triggered obstacles. This target N was located about two steps ahead. We assumed that peripheral vision could be used in this condition. In condition N+P (precise), subjects looked at the same target N, while they had to perform a high-precision stepping task, i.e. they had to step over the obstacles with minimal foot clearance, receiving acoustic feedback about their performance. In condition F (far), subjects looked at target F about four steps ahead. In this condition, we assumed that it was difficult to use solely peripheral vision. Condition F+P was the same as N+P but with target F. The order of the conditions was randomised.

4.3.4 Data analysis

For each subject and each condition, the median gaze-on-plane and the median head-on-plane were calculated for all 20 obstacle steps for the right and left side separately. Then, the right and left median gaze-on-plane and the right and left median head-on-plane were averaged. Several gaze-characteristics were derived from the sagittal data: (i) the amplitude of gaze- and head-movement downwards (gaze-amplitude, head-amplitude),

(ii) the time between the obstacle-trigger and the onset of gaze- and head-movement downwards (gaze-latency, head-latency), and (iii) the duration between the onset of gaze- and head-movement downwards and redirection upwards (gaze-duration, head-duration). To minimize subjectivity in determining these events, the analyses were performed by two investigators. If small differences between the events were found, the average was taken into the analysis. Large differences were analysed a third time.

On the basis of the gaze-amplitudes, three gaze-patterns were defined: Pattern 1 – the gaze was directed on the obstacle (amplitude ≥ 40 cm for the near target N or ≥ 155 cm for far target F); Pattern 2 – the gaze was directed towards the obstacle, but not completely (amplitude between the defined limits of gaze-pattern 1 and 3); and Pattern 3 - the gaze was not turned away from the given target (amplitude ≤ 10 cm for the near target N or ≤ 15 cm for the far target F). These borders were determined on the basis of 66 defined control measurements. Gaze-pattern 2 was additionally verified by studying the gaze-driven video images and the examination of the gaze-on-plane data for each individual obstacle step, before calculating the median. If gaze was not turned downwards (i.e. gaze-pattern 3), amplitude and duration were set to 0 cm and 0 s, respectively, while latency was defined as a missing value.

Most data were not normally distributed and the group sizes were small, therefore, nonparametric statistical tests were used. The three gaze-patterns were considered as ordinal data. For the pair-wise comparison between the two groups, the Mann-Whitney-U Test was used with a significance-level $p < 0.05$.

4.4 Results

Two of the 56 data-sets (14 x 4 conditions) could not be analysed completely due to technical problems.

In the high-precision condition, more participants turned their gaze downwards. However, no differences in gaze-pattern were observed between the healthy subjects and vestibular patients in any condition. In line with these findings, we also observed no significant differences in the gaze parameters, such as gaze-amplitude, -duration, and -latency (Table 4.1). Furthermore, vestibular patients showed also no significant differences in the head-movement parameters (head-amplitude, -latency and -duration) compared to healthy subjects. Only in condition N, the p-value of 0.08 showed a tendency that the vestibular patients moved their head earlier downwards than healthy subjects. However, the median gaze-latency, which is a combination of eye- and head-movement, was almost the same in the patient and in the healthy group (Table 4.1).

Both the healthy subjects and vestibular patients could minimize foot clearance during the high-precision conditions well and the foot clearance did not differ between the two groups (Table 4.1).

Overall, we found no significant differences in gaze behaviour and task performance between the groups (see Table 4.1).

Table 4.1: Head-movement and gaze behaviour parameters for each condition

Condition	Parameter	Vestibular patients	Control group	p-values
N	Gaze-Pattern	Number of subjects	Number of subjects	
	1	1	4	0.44
	2	3	2	
	3	8	8	
	Gaze-Amplitude	2 [0 - 25] cm	6 [0 - 67] cm	0.32
	Gaze-Latency	0.68 [0.44 - 1.29] s	0.70 [0.48 - 1.68] s	0.56
	Gaze-Duration	0.30 [0.00 - 0.89] s	0.35 [0.00 - 1.00] s	0.79
	Head-Amplitude	6 [0 - 40] cm	10 [0 - 29] cm	0.94
	Head-Latency	0.65 [0.33 - 1.06] s	1.16 [0.52 - 1.89] s	0.08
	Head-Duration	0.20 [0.00 - 0.84] s	0.37 [0.00 - 0.74] s	0.92
	Foot clearance	7.0 [6.5 - 9.0] cm	6.8 [5.9 - 8.3] cm	0.42
N+P	Gaze-Pattern	Number of subjects	Number of subjects	
	1	6	6	0.66
	2	4	3	
	3	3	5	
	Gaze-Amplitude	30 [12 - 86] cm	37 [0 - 94] cm	0.88
	Gaze-Latency	0.49 [0.42 - 1.15] s	0.44 [0.25 - 1.73] s	0.78
	Gaze-Duration	0.95 [0.56 - 1.31] s	0.75 [0.00 - 1.00] s	0.16
	Head-Amplitude	47 [0 -72] cm	36 [15 - 51] cm	0.78
	Head-Latency	0.55 [0.41 - 0.97] s	0.65 [0.52 - 1.96] s	0.26
	Head-Duration	0.69 [0.00 - 1.12] s	0.83 [0.46 - 1.11] s	0.63
	Foot clearance	4.0 [3.0 - 5.0] cm	4.2 [2.8 - 6.6] cm	0.36
F	Gaze-Pattern	Number of subjects	Number of subjects	
	1	2	2	0.54
	2	3	5	
	3	9	7	
	Gaze-Amplitude	10 [0 - 43] cm	33 [1 - 133] cm	0.35
	Gaze-Latency	0.51 [0.37 - 1.67] s	0.61 [0.42 - 0.75] s	0.71
	Gaze-Duration	0.35 [0.00 - 0.97] s	0.27 [0.09 - 0.81] s	0.82
	Head-Amplitude	3 [0 - 38] cm	38 [14 - 67] cm	0.13
	Head-Latency	0.89 [0.43 - 1.63] s	0.57 [0.49 - 1.62]s	0.62
	Head-Duration	0.06 [0.00 - 0.67] s	0.44 [0.16 - 0.90] s	0.18
	Foot clearance	8.0 [7.5 - 9.0] cm	6.3 [5.2 - 10.2] cm	0.29
F+P	Gaze-Pattern	Number of subjects	Number of subjects	
	1	7	7	0.81
	2	2	2	
	3	4	5	
	Gaze-Amplitude	164 [0 - 192] cm	159 [0 - 194] cm	0.98
	Gaze-Latency	0.98 [0.37 - 1.58] s	0.50 [0.38 - 0.89] s	0.50
	Gaze-Duration	0.66 [0.00 - 1.11] s	0.72 [0.00 - 1.31] s	0.86
	Head-Amplitude	78 [15 - 121] cm	54 [0 - 131] cm	0.71
	Head-Latency	1.19 [0.48 - 1.67] s	0.71 [0.40 - 1.36] s	0.34
	Head-Duration	0.83 [0.42 - 1.07] s	0.69 [0.00 – 1.00] s	0.58
	Foot clearance	5.0 [4.0 - 5.5] cm	4.7 [3.0 - 6.4] cm	0.41

Results and p-values are listed. Pattern 1 – gaze-turn on the obstacle, patter 2 – gaze-turn into the direction of the obstacle, pattern 3 – no gaze-turn downwards. Values between brackets show inter-quartile-ranges.

4.5 Discussion

The aim of the present study was to investigate whether patients with a complete unilateral vestibular dysfunction modified their gaze behaviour when avoiding a shortly announced obstacle. We found no modified gaze behaviour or altered head-movements in these patients, even under specific conditions in which high-precision stepping was performed or peripheral vision was reduced.

In a previous study where we applied the exact same protocol, we found different gaze behaviours between healthy elderly and young subjects. The elderly subjects focused later and longer on the obstacle than the younger subjects, which was in line with the literature (Chapman and Hollands, 2006; Di Fabio et al., 2003), and indicated that this protocol could detect changes in visual strategies between different groups.

Our vestibular patients showed no problems in accomplishing the locomotor tasks successfully. The foot clearance appeared equal between the healthy subjects and the patient group. Even the fear of falling appeared minimal in the patient group. Only one patient desired to be secured with the safety harness, without depending on it during the experiment. This obviously good performance is in line with improvements in postural stability during standing (Parietti-Winkler et al., 2006), gait velocity and gait deviations (Borel et al., 2004) after unilateral surgical removals of vestibular organs. However, we wanted to know if such good performance was based on a compensation related to altered gaze behaviour. As we could not find different strategies of gaze behaviour in the patients (for example prolonged looking downwards to the obstacle), one can assume that they did not need increased visual input – at least in the present obstacle-avoiding-task. We found no differences in head-movements as well, indicating that patients did not have any difficulty with vertical head-movement nor needed to look at a stable target in front of them for stabilisation.

The difficulty level of the obstacle-task might have influenced the results remarkably. In the current study, only vertical gaze-movements were induced and there was no different gaze-movement necessary for looking to the right or left obstacle. During a short interview, our patients reported to experience more difficulties in their daily life during horizontal head-rotations such as looking over their shoulder. Possibly, the vertical head-movement was not that challenging for patients with unilateral vestibular deficit.

Furthermore, we assume that the vertical head-movement produced a vestibular stimulus, as head-movement influence the center of pressure during standing (Buckley et al., 2005; Fukushima et al., 2008). However, the intentionally induced, relative slow head-movements during crossing the obstacle might have caused too weak and predictable vestibular stimulation, and did not affect visual strategies. On the other hand, all subjects walked at a relative slow speed. Indeed, patients with a vestibular disorder performed better during faster walking (Borel et al., 2004) or during running compared to walking (Brandt, 2000). Thus the slow speed in the present study should be quite challenging.

In conclusion, this study has shown that patients with a unilateral vestibular deficit are able to perform an obstacle avoidance task without any problems even during a high-precision locomotor task. The lack of adapted gaze behaviour and head-movements leads to the assumption that these patients compensate the loss of vestibular function of one side by the intact function of the other side and therefore do not require increased visual input.

5 Does pitch head-rotation during obstacle stepping affect balance by inducing a vestibular disturbance?[1]

Sandra Keller Chandra, Evelyne Dürr, Hubertus J.A. van Hedel

5.1 Abstract

Background: Large sagittal head-movements might be required to walk safely on challenging terrains or when wearing multi-focal glasses. We investigated whether large pitch head-rotations could affect balance by inducing a vestibular disturbance**.** ***Methods:*** Eleven young and eleven elderly subjects walked on a treadmill and visually fixated a target about 2.5 m in front at shoulder-height. Repetitively, subjects had to step over an obstacle announced by an acoustic warning signal and were asked to visually follow the obstacle. In the head-movement condition (HM), large pitch head-rotation was induced by ski-goggles which restricted the lower visual field. In the head stabilisation condition (HS), pitch head-rotation was restricted by a ruff and subjects could visually follow the obstacle only by eye-movements. Both conditions were additionally performed with induced galvanic vestibular stimulations (GVS) simulating forward head-movements (HM+GVS, HS+GVS). Analysed were: (i) HS vs HM, (ii) HS vs HM+GVS, and (iii) HS+GVS vs HM. Prior to, during, and after each obstacle step, seven double and six single stance phase durations were investigated in each group. In addition, vertical foot clearance and number of touched and dropped obstacles were recorded. *Results:* Elderly subjects elongated the single stance phase during obstacle crossing in the conditions with large pitch head-rotations. In the young group, two double stance phases and one single stance phase after the obstacle crossing were significantly shorter in HM+GVS than in HS. *Conclusion:* It is unclear whether voluntary pitch head-rotations can induce a vestibular disturbance. It appeared that the adaptive locomotor task performance in the elderly subjects was predominantly affected by visual and attentional disturbances. In the young subjects, it was influenced by restricting head-movements.

[1] Measurements in this project were conducted by Evelyne Dürr (master student) with support by Sandra Keller Chandra. Analyses were conducted by Sandra Keller Chandra. The manuscript was written by Sandra Keller Chandra and revised by the co-authors.

5.2 Introduction

The risk of elderly people wearing multifocal glasses to fall is twice compared to non multifocal glasses wearers (Lord et al., 2002). The lower segments of these glasses, determined for near vision, cause impaired contrast sensitivity and depth perception of the lower visual part, which is crucial for safe locomotion over uneven terrain or obstacles (Lord et al., 2002; Marigold and Patla, 2008a). For getting essential visual inputs with good acuity, large head-movements downwards (pitch head-rotation) might be necessary. However, Menant et al. (2009) could show that multifocal glasses wearers did not increase pitch head-rotation when stepping over an obstacle. This in turn affected safety, as it resulted in more obstacle touches. The question is why these subjects avoided the necessary large pitch head-rotation.

During standing, head-movements influence the postural stability by increasing body sway indicating a decrease in balance (Buckley et al., 2005; Fukushima et al., 2008). As this effect is also shown during stable constant visual inputs, it may be assumed that the postural instability by head-movements is caused by vestibular disturbances. However, as postural stability is also influenced by eye-movements and retinal slip (Edwards, 1946; Paulus et al., 1984), the question arose, whether a voluntary pitch head-rotation during walking over an obstacle affects balance mainly by inducing a vestibular disturbance or by changing the visual input.

During locomotion, the duration of double stance phases is an informative and sensitive parameter about gait performance, for example, the double stance phase was elongated in healthy elderly people compared to young subjects (Mbourou et al., 2003; Winter et al., 1990) and in elderly multi-fallers compared to non-fallers (Lord et al., 1996). Moreover, Hill et al. (1999) could show that the duration of double stance phases may be a variable associated with the prediction of multiple fallers. So, by elongating the double stance phase, stability may be increased to adjust for more challenging situations.

In this study, we investigated the influence of pitch head-rotation on gait parameters and performance during an obstacle avoidance task in healthy subjects. In addition, the influence of galvanic vestibular stimulation (GVS), simulating a forward head-movement (Cauquil et al., 1998) and specifically interfering with the vestibular system, was integrated in the study. Thus, comparisons between various conditions with or without pitch head-rotation and / or GVS were possible. We hypothesised that a pitch head-rotation would increase the double stance phases as an indicator for a disturbance of postural balance and decrease the performance of obstacle avoidance showing an augmented number of touched obstacles. If the pitch head-rotation is a vestibular disturbance, the induced GVS might influence the gait parameters and obstacle avoidance performance similarly as the pitch head-rotation. As elderly people show an altered postural stability (Koceja et al., 1999; Wolfson et al., 1992) and an increased risk of falling (Blake et al., 1988; Buatois et al., 2006), we investigated both young and elderly subjects.

5.3 Methods

5.3.1 Participants

The experiment was approved by the Cantonal Ethic Commission Zurich and the participants gave informed and written consent prior to data collection. Twenty-two healthy subjects participated, eleven young subjects (10 women, 1 man; average ± SD: 24.6 ± 2.1 years; range 18 - 30 years), and eleven elderly subjects (10 women, 1 man; 72.0 ± 5.0 years; range 65 - 83 years). All subjects performed sport exercises two to four times a week (the elderly were recruited from a sport group).

5.3.2 Experimental setup

Treadmill with obstacle machine

An obstacle machine (ALEA Solutions, Zurich, Switzerland) was placed next to a split-belt treadmill (Woodway, Weil am Rhein, Germany) on one side of subjects enabling them to step with their dominant leg over a foam stick 18 cm above floor level without changing their gait rhythm (Erni and Dietz, 2001). The obstacle was triggered by the heel strike one step cycle (two steps) before obstacle crossing. The heel strike was detected by force sensors (Kistler, Winterthur, Switzerland) located under the treadmill and was accompanied by an acoustic warning signal. The obstacle moved with the same speed as the treadmill (0.75 m/s), folded up at the end of the treadmill, and moved back into the starting position in front of the subject. The obstacle folded back or was released when subjects touched it. Additionally, subjects were secured by a harness mounted on the ceiling for preventing a fall but attached loose enough to not influence task performance. Infrared sensors attached on the obstacle machine could measure vertical foot clearance. Touched and dropped obstacles were automatically recorded.

Experiment

Subjects had to visually fixate a target about 2.5 m in front of them on the level of their shoulders. After the warning signal, they were asked to turn their gaze downwards for looking at the obstacle during stepping over it. In the conditions in which we induced large head-movement downwards, subjects wore customised ski-goggles preventing information from the lower visual field (Fig. 5.1A). For the conditions with stabilised head, subjects wore a ruff, so they were only able to look downwards into the direction of the obstacle by eye-movements (Fig. 5.1B). The induced or suppressed head-movements were validated using a video-analysing program (ClickJoint, ALEA Solutions GmbH, Zurich, Switzerland) (Fig. 5.1).

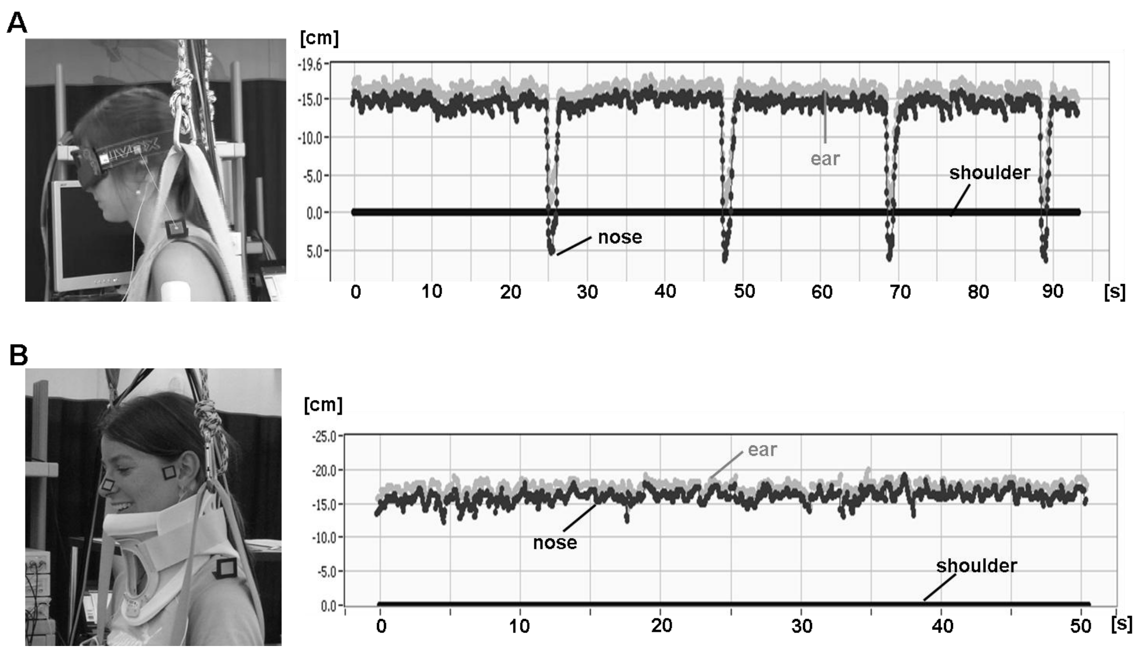

Figure 5.1: Head-movement and head stabilization conditions. A: Condition with large head movement (HM) caused by ski goggles with restricted lower visual field. B: Head stabilization condition (HS) caused by a ruff. The corresponding trajectories show the relative movements of three markers on the eye (in the HM-condition) or nose (in the HS-condition), the ear and the shoulder. For this evaluation, a video-analyzing system from ALEA Solutions (Zurich, Switzerland) was used.

Galvanic vestibular stimulation

Two Compex2 Motion Stimulators (Compex Motion SA, Ecublens, Switzerland) with modified software (Keller et al., 2002) were used for GVS. To simulate a forward head-movement in the sagittal plane, a double monaural stimulation was induced (Cauquil et al., 1998). Two small cathodal surface electrodes (Ambu Neuroline 700) were placed behind the ears on the processi mastoidei, two anodale electrodes (50 x 50 mm, Ambu A/S, Denmark) were placed on the arms. A stimulation of 1.5 mA (current flow) was induced assuming to be high enough as Cauquil et al. (1998) already showed responses to double monaural GVS lower than 1 mA. The GVS occurred on the same heel strike as the obstacle was triggered (one step cycle before crossing the obstacle) and lasted 1.5 s (certainly until after the obstacle crossing step).

5.3.3 Protocol

First, the dominant leg was determined and subjects were allowed to get used with walking on the treadmill and stepping over the obstacle. The electrodes for GVS were attached and a first stimulation during standing was induced to prepare subjects for the sensation. Subjects had to pass two trials (randomised order) with two conditions. In the head-movement-trial (HM), subjects had to wear ski-goggles which restricted the lower visual field; in the head-stabilised-trial (HS) they wore a ruff. In each trial, subjects had to pass two conditions: (i) stepping over obstacle with GVS (HM+GVS or HS+GVS) and (ii) stepping over obstacle without GVS (HM or HS). In each trial, each condition was applied 15 times resulting in 30 obstacle-steps in one trial. These obstacle-steps were randomly triggered at time intervals varying between 20 to 25 s. One trial lasted about 15 minutes. Finally, subjects filled-out a questionnaire about their subjective feeling during the trials, their balance in daily life, their falls in the past, and their daily physical activities.

5.3.4 Data analysis

Data were cut 3.5 seconds before and 7 seconds after each obstacle-trigger. Markers were set on each heel strike and toe-off of the force-trajectories for detecting the duration of seven double stance phases (DStr, DS-1, DS1, DS2, DS3, DS4, DS5) and six single stance phases (SS-1, SS0, SS1, SS2, SS3, SS4). The timing of the double and single stance phases relative to the obstacle step is illustrated in Fig. 5.2. The median value over all 15 obstacle steps for each corresponding double stance phase and single stance phase in the same condition was calculated.

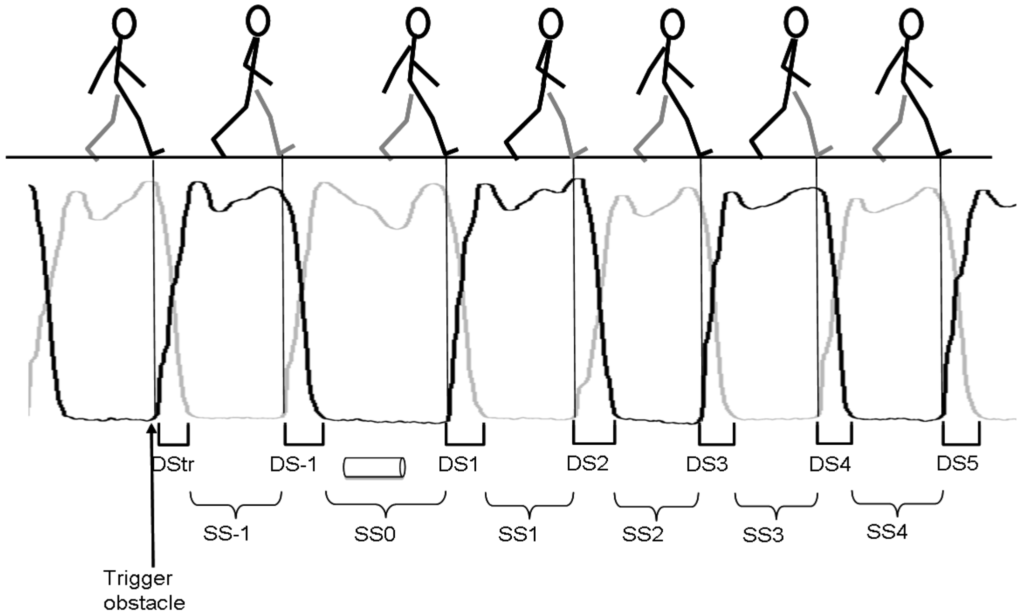

Figure 5.2: Double stance phases (DS) and single stance phases (SS) in relation to the triggered obstacles. The swing phase over the obstacle ( ) was defined as zero (SS0). SS and DS before obstacle-crossing were defined as minus. DStr (DS-trigger) started with the heel strike on which the obstacle was triggered.

The performance of the obstacle avoidance was identified by foot clearance and number of touched and dropped obstacles. Finally, the questionnaires were evaluated.

The elderly and the young group were evaluated separately. We assumed that HS could be considered as the control condition. The following pair-wise comparisons between the conditions were chosen: (i) HS vs HM should answer the question if pitch head-rotation has an influence on the gait-parameters and on the obstacle avoidance performance. Here, HS was defined as the control condition. (ii) By comparing HS to HM+GVS the influence of an additional vestibular stimulation to the pitch head-rotation was investigated. If the pitch head-rotation represented mainly a vestibular stimulation, the GVS should not have any additional influence. In an additional third analysis, we compared HS+GVS to HM, which should support the question if pitch head-rotation implied a vestibular disturbance, i.e. there should be no difference between these two conditions. If the HM condition shows different results to HS+GVS, it may be assumed that the head-movement implies other disturbances than vestibular ones, for example effects from the changing visual input. Due to the small group sizes and the distribution of the data, non-parametrical statistical tests were applied. For within-subjects comparisons, the Wilcoxon signed rank test was used for single and double stance phase durations, the Fisher's exact test was applied to the amount of touched and dropped obstacles. To adjust for multiple comparisons, the significance-level was set at $p < 0.017$; $p < 0.033$ was interpreted as a tendency.

5.4 Results

Young subjects reported no falls in daily life. In the elderly group, three subjects reported a fall in the previous one year (one subject two falls, two subjects one fall); one subject had one fall in the previous three months.

Most subjects described the sense of GVS as noticeable but not painful (eight young, six elderly subjects), two elderly subjects hardly sensed the GVS, three elderly and three young subjects described the GVS as little painful.

Most subjects (seven subjects from each group) reported more sensation of disturbance by the GVS in the head-movement conditions with the goggles than in the head stabilisation condition with the ruff. Only three young subjects reported the opposite. One young and four elderly subjects reported the same sensation of disturbance in both conditions.

5.4.1 Comparison HS vs HM

The elderly group showed no different duration of double stance phases (Fig. 5.3A). However, the duration of the single stance phase SS0 was longer in the HM than in the HS condition ($p = 0.004$) (Fig. 5.3C). The performance of obstacle avoidance, i.e. foot clearance and number of touched or dropped obstacles, showed no differences (Fig. 5.4A, Table 5.1).

The young subjects also showed no different duration of double stance phases in HS and HM (Fig. 5.3B). SS2 tended to be shortened in the HM condition ($p = 0.018$) (Fig. 5.3D). In the obstacle avoidance performance, no differences between HS and HM were found (Fig. 5.4B, Table 5.1).

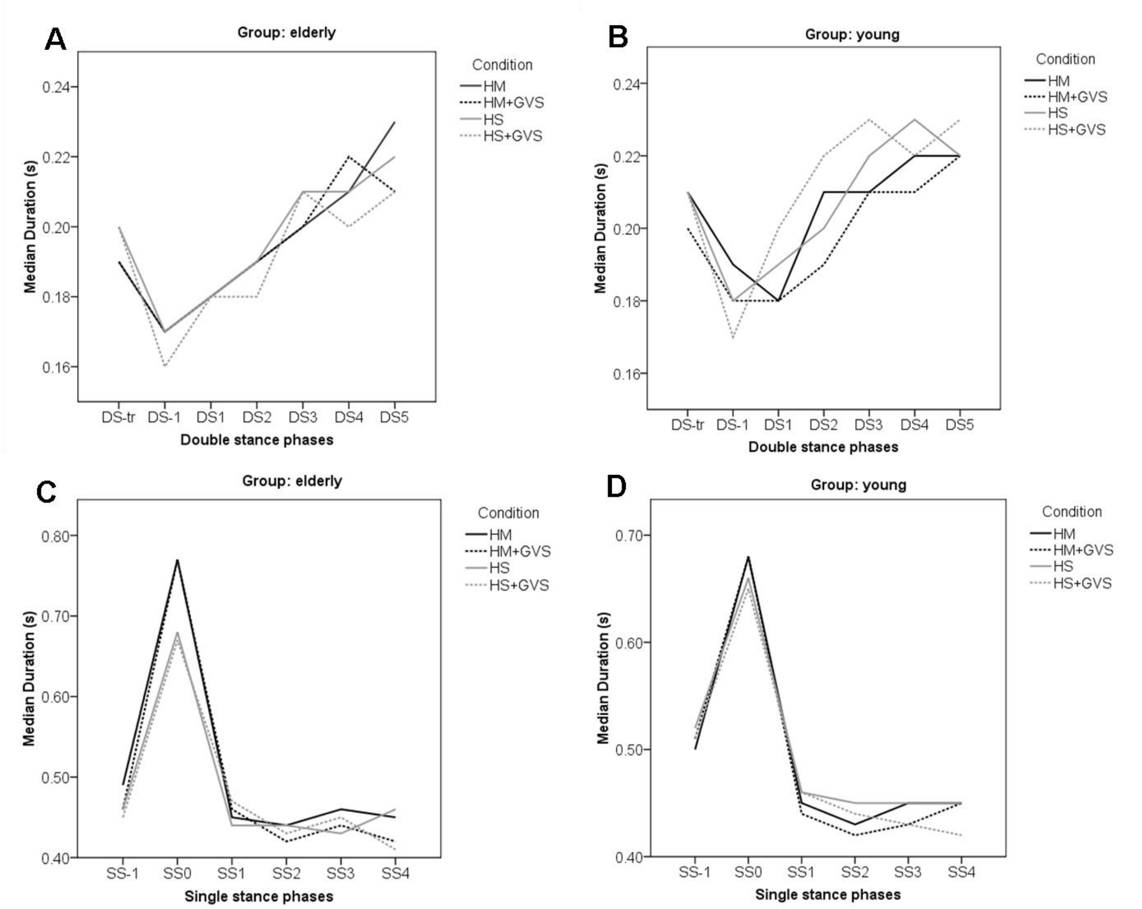

Figure 5.3: Duration of double stance phases (DS) (A and B) and single stance phases (SS) (C and D). Shown are the medians over all young subjects (A and C) and elderly subjects (B and D). HM = head movement condition, HM+GVS = head movement condition with galvanic vestibular stimulation (GVS), HS = head stabilisation condition, HS+GVS = head stabilisation condition with GVS. Please note the different scales of the y-axes between figures C and D.

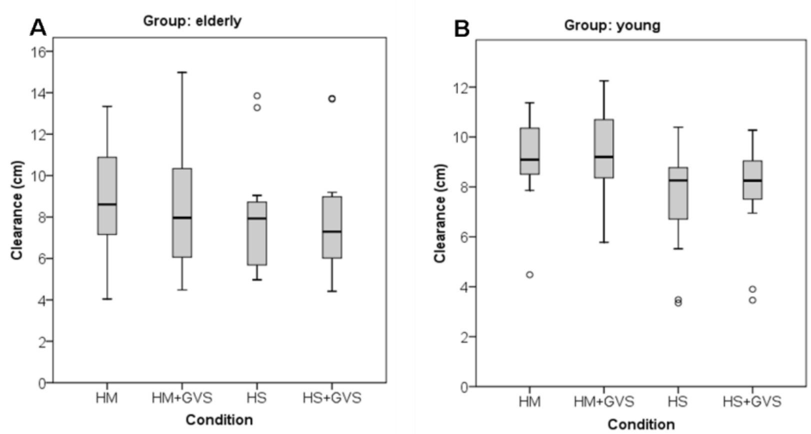

Figure 5.4: Vertical foot clearance in the elderly (A) and young (B) group. HM = head movement condition, HM+GVS = head movement condition with galvanic vestibular stimulation (GVS), HS = head stabilisation condition, HS+GVS = head stabilisation condition with GVS. Please note the different scales of the y-axes.

Table 5.1: Number of touched and dropped obstacles

Condition	Number of Subjects / Events	Elderly		Young	
		Touch	Drop	Touch	Drop
HM	Subjects	4	1	1	1
	Events	8	3	1	1
HM+GVS	Subjects	5	4	5	0
	Events	9	5	5	0
HS	Subjects	1	2	1	0
	Events	3	2	1	0
HS+GVS	Subjects	2	2	2	0
	Events	3	2	4	0

Listed is the number of subjects on which the numbers of touched and dropped obstacles were distributed. HM = head movement condition, HM+GVS = head movement condition with galvanic vestibular stimulation (GVS), HS = head stabilisation condition, HS+GVS = head stabilisation condition with GVS.

5.4.2 Comparison HS vs HM+GVS

No differences between HS and HM+GVS were found in the elderly group concerning the double stance phases (Fig. 5.3A). SS0 was shorter in HS than in HM+GVS ($p = 0.006$) (Fig. 5.3C). The performance of obstacle avoidance was not adapted (Fig. 5.4A, Table 5.1).

Young subjects showed shorter DS1 ($p = 0.006$), DS4 ($p = 0.010$), and SS2 ($p = 0.012$) in HM+GVS than in HS ((Fig. 5.3B & D). Additionally, they tended to cross the obstacles with a higher foot clearance in HM+GVS ($p = 0.021$) (Fig. 5.4B).

5.4.3 Comparison HS+GVS vs HM

In the comparison between HS+GVS and HM, elderly subjects showed no difference in double stance phases but SS0 was elongated in the HM condition ($p = 0.003$) (Fig. 5.3A & C). The obstacle avoidance performance showed no differences (Fig. 5.4A, Table 5.1).

Young subjects tended to shorten DS5 in the HM condition ($p = 0.027$) and to prolong SS0 ($p = 0.028$) and SS4 ($p = 0.024$) (Fig. 5.3B & D). No changed obstacle avoidance performance could be found (Fig. 5.4B, Table 5.1).

5.5 Discussion

In this study, we investigated four conditions during walking on a treadmill with an obstacle avoidance task. In HM, a large pitch head-rotation was induced. In HS, the head was stabilised by a ruff. In HM+GVS and HS+GVS, an additional galvanic vestibular stimulation was applied. Three comparisons were analysed separately in each group: (i) HS vs HM, (ii) HS vs HM+GVS, and (iii) HS+GVS vs HM.

In the elderly group, no difference in duration of double stance phases between the conditions could be detected. Consequently, as an elongated double support would indicate difficulties with balance (Hill et al., 1999), the pitch head-rotation during obstacle-crossing did not seem to induce imbalance. Surprisingly, the GVS did not cause any disturbances, too. In literature, there were no comparable studies found with applied bipolar binaural GVS during treadmill walking like in the present project. Investigations of Bent et al. (2000) and McFadyen et al. (2007) have shown lateral deviations in the direction to the anode during over-ground walking, but the applied GVS setup was bipolar binaural. However, large lateral deviations were inhibited during treadmill walking and the exactly foot placement concerning the lateral step width could not be detected with the methods used in the present study. In the mentioned study of McFadyen et al. (2007), also stance phases of each leg, as a sum of single and double stance phase, were analysed. They did not find any influence of the GVS during over-ground locomotion with an obstacle task under normal visual conditions, nor did they observe any differences in foot clearance which was confirmed in the present study.

Elderly subjects showed a significant elongated SSO (the single stance phase during crossing the obstacle) in both conditions with a pitch head-rotation compared to stabilised head conditions. There are two possible explanations for this result: First, the increased gaze turn downwards provoked the elderly subjects to step more precisely over the obstacle and therefore, they used more time resulting in a longer single stance phase. Though, the number of touched obstacles was augmented in the conditions with pitch head-rotation (Table 5.1) (results were not significant). It would be expected that a more intensive visual guidance would avoid such touches. A second explanation for the elongated SSO in head-movement conditions may be the increased difficulty for elderly people to do two things at the same time (Chen et al., 1996; Melzer and Oddsson, 2004). The demanded large pitch head-rotation and the visual follow of the obstacle might cause a short “stop” in walking resulting in a longer single stance phase. Even if the treadmill continuously forces the subject to walk, such a short backpedalling is possible, especially during the low walking speed of 0.75 m/s.

In the group of young subjects, the pitch head-rotation in the HM condition also caused no altered double stance phases compared to HS. So, similar to elderly subjects, the voluntary downwards head-movement seemed to have no or not enough influence on the balance for young subjects. However, young subjects showed shorter double stance phases in the condition HM+GVS than in HS with significant differences in DS1 and DS4. This result is contrary to our expectations and a satisfying explanation is difficult. Figure 5.3A shows that the double stance phases in the conditions with head stabilisation were longer than the ones of head-movement conditions. Probably, in contrast to our assumption that the HS condition could be considered as the control condition, the ruff caused problems for young subjects as the natural head-movements during locomotion were restricted (Grossman et al., 1988; Pozzo et al., 1990). Elderly people show smaller head-movements during normal walking (Van Emmerik et al., 2005), which might have resulted in the smaller effects of restricted head-movement in this group. There were also some differences in the duration of single stance phases in the young group, however, the effects were not as clear as in the elderly group.

The successive increase in duration of the double stance phases after the obstacle step (see Fig. 5.3A & B) might suggest an increase in imbalance. However, it appeared to be a return to normal double stance durations during walking, as a comparison with normal steps during treadmill walking (without obstacle and without GVS) has shown.

In both groups, there could not clearly be shown that the pitch head-rotation during crossing the obstacle induced a vestibular disturbance. In the elderly group, the additional GVS in the comparison HS vs HM+GVS did not lead to further alterations in gait parameters than in the comparison HS vs HM. However, as in the latter comparison no differences in the duration of double stance phases could be found, the question if the pitch head-rotation indicated a vestibular disturbance remained unanswered. In the young subjects, HS vs HM+GVS provoked other differences in gait parameters than HS vs HM. So, that could lead to the conclusion that the pitch head-rotation by itself did not induce (strong enough) vestibular disturbances. Actually, as the detected response of changed duration of double stance phases in HM+GVS was unexpected and could not be explained, the conclusion failed.

Furthermore, in both groups, the comparison HS+GVS vs HM showed differences. As a consequence, the pitch head-rotation could not be equated with the GVS simulating a forward head-movement. However, the demanded pitch head-rotation was a voluntary movement, whereas the induced GVS was unexpected for the subjects as the conditions (obstacle-step with or without GVS) and the time between two obstacle steps were randomised. Vallis and Patla (2004) investigated the influence of a yaw head-rotation on gait performance in two experiments, one with a self-induced, and the other with an unexpected head-movement. Even if the responses of gait performance in these two experiments were not statistically compared to each other, the results indicate different outcomes as steps were wider and lateral trunk-movements occurred later after the unexpected head-perturbation than after voluntary head-movement. In further studies about postural response to external perturbations, different center of pressure displacements were measured with expected and unexpected stimuli (Caudron et al., 2008; Jacobs et al., 2008). Hence, the diverse awareness of pitch head-rotation and GVS in the present study may lead to altered responses.

A problem of the present study might be the analysed comparisons. We assumed that the head stabilisation condition HS could be chosen as a control condition, i.e. the ruff would have no influence on gait parameters. However, young subjects seemed to have some problems with the induced head stabilisation. Therefore, comparisons with HS as a control condition could falsify results. A comparison to a natural obstacle crossing condition without a ruff would have been more reasonable.

In a study from (Yamamoto et al., 2002), the effect of a caloric vestibular stimulation on gait parameters, head-, and trunk-movements during walking on a treadmill was investigated. They found enlarged lateral translation and yaw rotation of head and thorax toward the stimulated side, but no changes in vertical translation and pitch rotation nor any altered stride cycle, stride length or stance phase between pre- and post-stimulation. Obviously, treadmill walking inhibits adaptations of gait parameters to vestibular stimulations, which may contribute to the inconclusive outcomes found in the present study. Indeed, treadmill walking has some different characteristics compared to over-ground walking. Some studies have compared these two methods, but their outcomes are not in agreement. While some studies reported no alterations in duration of double stance phases (Lee and Hidler, 2007; Riley et al., 2007), others reported tendencies for longer (Murray et al., 1985) or even significant shorter (Stolze et al., 1997) double stance phases. However, the fact that during treadmill walking a remarkable movement break is not possible without resulting in a fall may have highly influenced the outcome of gait parameters in the present study. During over-ground walking, a slowdown or even a stop and therefore a prolonged double stance phase is an option to regain balance. During treadmill walking, only short variations in the duration of double stance phases are possible, because the treadmill keeps on running.

5.6 Conclusions

The pitch head-rotation during stepping over an obstacle could not be identified as a clear vestibular disturbance. In fact, the elderly group seemed to be rather influenced by visual or attentional disturbance caused by the pitch head-rotation. In the young group, the influence of the ruff as a restriction of natural head-movements during walking was discussed. Especially in the elderly group, single stance phases showed more alterations than double stance phases. The duration of double-stance phases during treadmill walking as an indicator for imbalance may not be the best parameter. An investigation of pitch head-rotation during over-ground walking might bring more answers, because an elongation of double stance phases to stabilise imbalance might be more likely.

6 General discussion

The aim of this thesis was to investigate the gaze behaviour during walking over obstacles. We were interested in subjects with impaired sensory inputs and expected altered gaze behaviour compared to healthy subjects. Therefore, we investigated three groups: (i) elderly people, (ii) patients with a deficit in somatosensory inputs after a spinal cord injury, and (iii) patients with a vestibular loss. In a fourth study, we investigated the influence of large pitch head-rotations on gait parameters during an obstacle avoidance task with the question if this head-movement in the sagittal plane induces vestibular disturbances.

6.1 Main findings

The elderly group showed different gaze behaviour than younger subjects during walking on a treadmill with an obstacle avoidance task. Overall, they turned their gaze earlier and for longer time to the obstacle. So, even though the constitution of the elderly subjects was quite good and they reported no falls, age-related diminished sensory deficits (Cohen et al., 1996; Goble et al., 2008; Rosenhall and Rubin, 1975; Shumway-Cook and Woollacott, 2001) led to an augmented dominance of visual inputs. As a consequence for daily life, elderly people should try to ensure that the visual input of the environment is adequate, i.e. the illumination and the acuity (if necessary by wearing glasses) are sufficient. They should be cautious, for example, during walking around with multifocal glasses because of the blurring of distant objects on the floor in the lower visual field (Lord et al., 2002). On the other hand, training of vestibular and somatosensory systems, for example balance training, could increase the availability of appropriate afferent information (Sihvonen et al., 2004; Tsang and Hui-Chan, 2004).

In the study with iSCI-patients, the results deviated from our expectations. Due to the somatosensory deficits of these patients, we hypothesised an augmented need for visual input during stepping over the obstacle, i.e. more and longer gaze-turns to the obstacle, especially in the high-precision condition. However, results rather tended to a higher prioritisation of visual stability resulting in longer visual fixation of the given stable target in front of the subjects and, accordingly, later gaze-turns downwards. This gaze behaviour of iSCI-patients is comprehensible. Impaired somatosensory inputs and, additionally, potential impairments of the vestibulo-spinal tract (Liechti et al., 2008) may lead to deficits in balance (Lemay and Nadeau, 2010). Stable visual inputs increase postural balance (Edwards, 1946; Paulus et al., 1984). In the present study, the requirements on balance obviously exceeded the need for visual input of the obstacle for safe avoidance and a focus on both requirements might exceed the capacity of the iSCI-patients (Mulder and Geurts, 1993). This would explain the reduced flexibility of gaze behaviour. Furthermore, an exceeded capacity was also shown by the tendency of more touched obstacles in the dual task condition.

The study about gaze behaviour in iSCI-patients indicates that the augmented need of visual input for postural stabilisation may lead to the higher risk of falls (Brotherton et al., 2007; Wirz et al., 2010). Balance training independent from visual input (for example with closed eyes) might be beneficial since improved postural stability could allow more flexibility in visual behaviour, i.e. a gaze turn to a difficult terrain. However, most results in this study showed only tendencies, probably due to the variability between the injuries of the patients and their impairments.

The lack of altered gaze behaviour in the patients with complete unilateral vestibular loss was quite unexpected and surprising. Probably, the obstacle avoidance task which required head-movements only in the sagittal plane was too simple for these patients. However, we assumed that a head-movement in the sagittal plane, i.e. a pitch head-rotation, causes vestibular disturbances and therefore, vestibular patients would avoid it. In an additional study, we investigated the influence of pitch head-rotation during stepping over obstacles on gait parameters. The results did not give any clear evidence that the head-movement causes vestibular disturbances. There was rather a hint that the changing visual input during a pitch head-rotation had an influence on the obstacle step, especially in the elderly group. This result would be in line with the augmented importance of visual input found in the study of this thesis about gaze behaviour in elderly subjects.

6.2 Limitations and Outlook

Afferent, partly diminished sensory inputs and behavioural outputs during different locomotion tasks are interacting in a complex way. Thereby, many facts may influence the results. (i) With the obstacle avoidance task during walking on a treadmill, we had the possibility to investigate repetitive obstacle steps under stable conditions. The acoustic announcement of the obstacles and the given target on the floor subjects had to look at in-between two triggered obstacles prevented a permanent gaze on the obstacles, simulating daily situations (Patla and Vickers, 1997). However, treadmill walking is different to over-ground walking. There is no optic flow during walking on a treadmill (Patla, 1997; Prokop et al., 1997). The gait velocity is given and a sudden slow down or a walking break is not possible. There might be a decrease of visual dependency as there is no need to decide where to step. Some studies have shown altered durations of double stance phases during treadmill walking compared to over-ground walking (Murray et al., 1985; Stolze et al., 1997). So, over-ground walking with the chosen subjects and under corresponding conditions as in the present studies might be meaningful. A comparison between gaze behaviour during treadmill and during over-ground walking could bring additional knowledge about the variable outcomes of these two methods.

(ii) In some cases, measurements with the video-oculograph (VOG) were unstable when the pupils were covered too much by the eyelids during looking downwards. Hence, the video cameras could not detect the pupils and lacks in the gaze-trajectory occurred. Furthermore, by the median-calculation over all obstacle steps in one condition and one subject, the values of gaze- and head-movements could obtain uncertainty resulting in a blurring of the trajectory. So, the defining of the exact marker points for looking downwards and upwards could be difficult. However, to reduce subjectivity for setting the markers, analyses were done at least twice by two independent investigators.

(iii) Participants knew that the focus of the study was the investigation of gaze behaviour. A switch of their attention to the own gaze behaviour and therefore a possible discrepancy to their natural gaze behaviour could not be excluded. Results might also be influenced by the mood of the participants as gaze behaviour can be changed by cognitive distraction or anxiety (Janelle et al., 1999; Nieuwenhuys et al., 2008). However, during measurements, we intended to reach automaticity of the task by enabling subjects to become familiar with the obstacle stepping prior to the measurements and by a high number of repetitions.

(iv) One of the most important points in a study with humans is an adequate sample. A randomised recruitment of healthy subjects may be easy, but it is often quite hard to reach a homogeneous patient group with enough participants. High variability of the level of disease can cause large distribution of the results and therefore, statistical significance may be reduced. In this thesis, constitutional condition of iSCI-patients was quite variable and it was not possible to recruit more patients according to the in- and exclusion criteria. In the study with vestibular patients, the participants compensated their unilateral vestibular loss very well resulting in a good performance. No patient had reported multiple falls in daily life. So, further investigations with more affected patients including fallers or with a more challenging requirement of the task, as, for example, induced yaw head-rotations, might have brought larger significant differences.

6.3 Conclusions

In the three studies with elderly subjects, iSCI-patients, and vestibular patients we intended to investigate the influence of diminished sensory inputs on gaze behaviour during an obstacle avoidance task. The hypothesis that these sensory deficits were compensated with altered gaze behaviour could only partly be verified. The elderly participants were healthy and had no specific deficits of afferent inputs apart from the common age related sensory reduction. Compared to younger subjects, they were more dependent on visual inputs showing earlier and longer gaze-turns to the obstacles. Furthermore, they could use less peripheral vision. In the study with iSCI-patients, the influence of impaired somatosensory input was investigated. Patients tended to show less flexible gaze behaviour than age-matched healthy subjects. They seemed to be more dependent on the stabilising visual input by the given target in-between two triggered obstacles resulting in a tendency of later gaze-turns downwards. In the study with vestibular patients and the intention to investigate the unilateral loss of vestibular input, we could detect no altered gaze behaviour compared to age-matched healthy subjects. In the fourth study, we investigated if a pitch head-rotation during walking over an obstacle causes a vestibular stimulation resulting in disturbed dynamic balance. The question could not clearly be answered. There were indications that young subjects were influenced rather by enforced head stabilisation and elderly subjects by visual disturbances caused by the pitch head-rotation.

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- Gaze behavior during walking over obstacles in vestibular patients. 6th ZIHP Symposium (Zurich Center for Integrative Human Physiology), Zurich, August 2010

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